HANDBOOK
OF
ELEMENTARY
PHYSICS

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Н. И. КОШКИН и М. Г. ШИРКЕВИЧ

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На английском языке

N. KOSHKIN and M. SHIRKEVICH

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PREFACE

The compilers of the present handbook, N. I. Koshkin and M. G. Shirkevich, are experienced Soviet teachers.

The handbook covers all the main subjects of elementary physics and contains information most frequently required in industry and agriculture.

Special attention has been paid to the choice of data on the latest developments in physics, such as semiconductors, ferroelectrics, nuclear physics, etc.

In addition to graphs and tables the book offers brief theoretical expositions, definitions of fundamental concepts and formulations of laws accompanied by explanations and examples.

The handbook is intended for wide circles of readers in various occupations, and for students with a background of secondary school physics.

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EXPLANATORY NOTES

Most of the tables are arranged in alphabetical order. Some, however, are arranged in the order of increasing or decreasing values of the tabulated quantity.

The numerical values of the quantities are given to two or three significant figures after the decimal point, which is sufficiently precise for most technical calculations.

The number of figures given after the decimal point varies in the tables. This is due to the circumstance that some substances can be obtained in the pure form, whereas others are complicated mixtures of substances. For example, the density of platinum is given to four significant figures: 21.46, whereas that of brass is given to within three units of the second significant figure: 8.4-8.7, since the density of brass varies within these limits depending on the composition of the given specimen

If the heading of a column in a table contains a factor, such as 10^n, this denotes that the values of the quantity in that column have been *increased* 10^n times; hence, to find the true values one must *divide* the values given in the table by this factor. For example, in the heading of the last column in Table 18: "Compressibility of liquids at different temperatures" (p. 44) the compressibility β has been multiplied by 10^6 ($\beta \times 10^6$ atm^{-1}). Thus, the compressibility of acetone, according to this table, is 111×10^{-6} atm^{-1}.

The notes to the tables give the conditions for which the values of the tabulated quantities are valid (if these conditions are not indicated in the heading of the table), as well as additional information on how to use the tables, etc.

If the physical significance of the tabulated quantity is not quite clear to the reader, he should refer to the relevant section: "Fundamental Concepts and Laws". This can be found with the help of the table of contents or the index at the end of the book. The appendices contain information on the units of measure of physical quantities, formulas for approximate calculations, and the values of some universal physical constants.

CHAPTER I

MECHANICS

When a body changes its position relative to other bodies it is said to be in *mechanical motion*. A change in the position of a body relative to other bodies is determined by a change in the distance between the points of the bodies. The unit of distance is the *meter* (m).

The meter is defined as a length equal to 1,650,763.73 wavelengths in vacuo of the orange radiation of krypton-86.

The unit of time is the *second**, defined as 1/31,556,925.9747 part of the tropical year 1900 (for uniformly passing time).

A. *KINEMATICS*

FUNDAMENTAL CONCEPTS AND LAWS

Kinematics is the study of the motion of bodies without regard to the cause of that motion.

The simplest moving body is a *point mass*, defined as a body whose dimensions can be neglected in describing its motion. For example, the annual motion of the earth about the sun can be regarded as the motion of a point mass, whereas the daily revolution of the earth about its axis cannot.

Every solid body can be regarded as a system of rigidly bound point masses. The path described by a moving body is called a *trajectory*.

According to the form of the trajectory we distinguish between *rectilinear* motion (the trajectory is a straight line) and *curvilinear* motion (the trajectory is a curve). We also distinguish between *uniform* and *non-uniform* motion.

---

* The *second* is more precisely defined by the U.S.S.R. State Standard GOST 9867-61.

1. Rectilinear Motion

Uniform motion is defined as motion in which a body traverses equal distances in equal time intervals. Uniform motion is characterised by its velocity. The *velocity of uniform motion* (v) is defined as the distance (s) traversed in unit time (t):

$$v=\frac{s}{t},$$

$$s=vt. \qquad (1,1)$$

Velocity is a vector quantity. It is characterised by magnitude and direction in space. The addition (composition) of velocities is performed according to the parallelogram law (addition of vectors). The units of velocity are: cm/sec, m/sec, km/sec, km/hour.

In non-uniform motion we differentiate between instantaneous and average velocity.

If a body passes over a distance Δs in the time interval from t_0 to $t_0+\Delta t$, then

$$v_{\text{av}}=\frac{\Delta s}{\Delta t}$$

is defined as the *average velocity* for the time interval Δt. In other words, if the body were moving uniformly with velocity v_{av}, it would cover the distance Δs in the time Δt. The *instantaneous velocity* at a given moment t_0 is defined as the limit of the ratio:

$$v_{t_0}=\lim_{\Delta t\to 0}\frac{\Delta s}{\Delta t}.$$

Motion in which the velocity receives equal increments in equal time intervals is called *uniformly accelerated*. The rate of change of the velocity is called the *acceleration* (a):

$$a=\frac{v_t-v_0}{t},$$

where v_t is the velocity at the time t and v_0 is the velocity at the initial time t_0. Acceleration is also a vector quantity. The units of acceleration are: cm/sec^2, m/sec^2, km/sec^2.

The velocity at any given moment is determined by the formula:

$$v=v_0+at, \qquad (1,2)$$

where v_0 is the initial velocity.

The acceleration may be positive (*accelerated motion*) or negative (*decelerated motion*).

The distance traversed in uniformly accelerated motion is given by the formula:

$$s=v_0t+\frac{at^2}{2}. \qquad (1,3)$$

The terminal velocity in uniformly accelerated motion is determined by the initial velocity, the acceleration and the distance traversed:

$$v^2=v_0^2+2as \qquad (1,4)$$

The motion of freely falling bodies is an example of rectilinear motion with constant acceleration. If we denote the height from which the body falls ($v_0=0$) by h, and the acceleration of free fall by g, then

$$h=\frac{gt^2}{2}.$$

2. Rotational Motion

The *circular motion of a point* about an axis is defined as motion in which the trajectory is a circle whose centre is on the axis and whose plane is perpendicular to the axis. The *rotational motion of a body* about an axis is defined as motion in which all the points of the body describe circular motion about this axis.

Uniform rotation is motion in which a body turns through equal angles in equal time intervals.

The *angular velocity* (ω) *of uniform rotation* is defined as the angle swept out in unit time:

$$\omega=\frac{\varphi}{t}, \qquad (1,5)$$

where φ, measured in radians, is the angle through which the body turns in a time t. The unit of angular velocity is the radian per second (rad/sec). The angular velocity may also be expressed in terms of the number of revolutions in unit time n, or the period of revolution T:

$$\omega = 2\pi n, \tag{1,6a}$$

$$\omega = \frac{2\pi}{T}. \tag{1,6b}$$

The *linear velocity* of a point in rotational motion is defined as the instantaneous velocity of the point. Its direction is tangent to the trajectory. The angular velocity ω is related to the linear velocity v by the formula:

$$v = \omega R, \tag{1,7}$$

where R is the distance from the point to the axis of rotation.

In the case of non-uniform rotation we distinguish between instantaneous and average angular velocities. If the body has turned through an angle $\Delta\varphi$ in a time from t_0 to $t_0+\Delta t$, then the *average angular velocity* (ω_{av}) for the time Δt is defined as

$$\omega_{av} = \frac{\Delta\varphi}{\Delta t}.$$

The limit of this ratio is, by definition, the *instantaneous angular velocity*

$$\omega_{t_0} = \lim_{\Delta t \to 0} \frac{\Delta\varphi}{\Delta t}.$$

Rotational motion in which the angular velocity receives equal increments in equal time intervals is called *uniformly accelerated*.

The *angular acceleration of uniformly accelerated rotation* (j) is defined as the rate of change of the angular velocity:

$$j = \frac{\omega_t - \omega_0}{t},$$

where ω_t is the angular velocity at the time t, and ω_0 is the initial angular velocity:

$$\omega_t = \omega_0 + jt. \tag{1,8}$$

In uniformly accelerated rotation the linear velocity v of any point of the body varies both in magnitude and in direction. The change in magnitude of the linear velocity is characterised by the *tangential acceleration*:

$$a_\tau = \frac{v_t - v_0}{t}, \tag{1,9}$$

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where v_t and v_0 are the linear velocities at the time t and at the initial moment of time. At any given point of the trajectory the direction of a_τ coincides with the direction of v. The tangential acceleration a_τ is related to the angular acceleration j by the formula:

$$a_\tau = jR.$$

However, even when a body is in uniform rotation the points of the body are in accelerated motion, for the direction of their velocity is continually changing. The acceleration of this motion is directed towards the axis of rotation (i. e., perpendicular to the direction of the linear velocity) and is called the *centripetal acceleration*:

$$a_c = \frac{v^2}{R} \qquad (1,10a)$$

or

$$a_c = \omega^2 R, \qquad (1,10b)$$

where v is the linear velocity, ω—the angular velocity, and R—the radial distance of the point from the axis of rotation.

The *total acceleration* of a point of a body in uniform rotation is

$$a = \sqrt{a_c^2 + a_\tau^2}. \qquad (1,11)$$

3. Motion of Bodies in the Earth's Gravitational Field

Fig. 1 illustrates the trajectories of bodies which are projected from point A near the surface of the earth with different velocities*. In all cases the velocity is directed horizontally. The trajectory is a *circle* if the velocity of the body v at point A is such that the acceleration of free fall g is equal to the centripetal acceleration $\frac{v^2}{R}$ (R is the radius of the trajectory, which can be taken equal to the radius of the earth). Hence

$$v = \sqrt{Rg} \approx 7.93 \text{ km/sec}.$$

If the velocity of the body at point A is greater than 7.93 km/sec but less than 11.2 km/sec, then the trajectory is an *ellipse*; the focus of the ellipse nearer to the point of departure (point

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[*] The resistance of the air is neglected.

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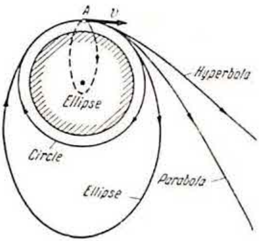

Fig. 1. Trajectories of bodies in the earth's gravitational field.

A) lies at the centre of the earth. (This ellipse is depicted by a solid line in Fig. 1). If the velocity of the body equals 11.2 km/sec, then the trajectory is a *parabola*. If the initial velocity is greater than 11.2 km/sec, then the trajectory becomes a *hyperbola*. In the last two cases the body leaves the earth and goes off into interplanetary space. The least velocity required for a body to leave the earth is sometimes called the *escape velocity*. The path of a body moving with velocity less than 7.93 km/sec represents an arc of an ellipse (dotted line in Fig. 1) whose distant focus coincides with the centre of the earth.

If the velocity is much less than 7.93 m/sec the path may be regarded as parabolic, and the acceleration of free fall may be considered constant in magnitude and direction.

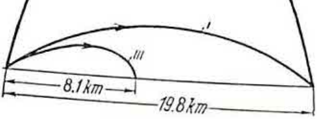

Fig. 2. Trajectories of bodies projected from the surface of the earth with velocity $v_0=550$ m/sec. Curve I – angle of projection $\alpha=20°$, curve II – angle of projection $\alpha=70°$, curve III – angle of projection $\alpha=20°$, with air resistance taken into account.

If a body is projected from the *surface of the earth* at an angle α with the horizontal, with an initial velocity v_0 much less than $v=7.93$ km/sec, then in this case, too, the acceleration of free fall may be considered constant in magnitude and direction, while the surface of the earth may be regarded as flat. The trajectory will then be a parabola (Fig. 2). The range (S) and the maximum height (H) are calculated by the formulas:

$$S=\frac{v_0^2 \sin 2\alpha}{g}, \qquad H=\frac{v_0^2 \sin^2 \alpha}{2g}, \qquad (1,12)$$

where v_0 is the initial velocity of the body.

The range will be the same for two values of the angle of projection: α_1 and α_2, where $\alpha_2=90°-\alpha_1$.

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The maximum range corresponds to the angle $\alpha=45^\circ$.

If the resistance of the air is taken into account the range and the height of the trajectory are less. For example, in the absence of air resistance a body thrown at an angle $\alpha=20^\circ$ with an initial velocity $v_0=550$ m/sec would have a range of 19.8 km, whereas a projectile fired at the same angle and with the same initial velocity would have a range of only 8.1 km.

TABLES

Table 1

Velocity of Motion of Different Bodies

Elevator in house	1.5-4.5 m/sec
Subway train	up to 75 km/hour
Electric locomotive VL-23	" 90-100 "
Automobile ZIL-110	" 140 "
Passenger train diesel locomotive TE-7	" 140 "
Torpedo boat	" 150 "
Passenger plane IL-14	" 415 "
Racing car (1947 world record)	" 634.2 "
Passenger jet plane TU-104	up to 1,000 "
Jet fighter plane	" 2,000 "
Jet plane "Nord 1,500 Griffon 02" (1959 world record)	" 2,330 "
Bullet at exit from gun muzzle	" 860 m/sec
Motion of electron beam over screen of television set KVN-49	" 2,500 "
Orbital velocity of artificial earth satellite	about 8,000 "
Cosmic rocket	more than 11,000 "
Velocity of earth on its orbit	" " 30,000 "
Electrons in cathode-ray tube	up to 10^8 "
Electrons in betatron	" " 3×10^8 "

Table 2

Acceleration of Different Bodies (Approximate Values)

Accelerated motion	Acceleration, m/sec²	Decelerated motion	Deceleration, m/sec²
Subway train	1	Emergency braking of automobile	4-6
Racing car	4.5	Landing jet plane	5-8
Elevator in house	0.9-1.6	Parachute opening when rate of fall is 60 m/sec	about 60
Passenger train	0.35		
Tramcar	0.6		
Shell in gun barrel	100,000		

Table 3

Escape Velocities in the Solar System

Mean radius of the earth 6,370 km. Mass of the earth 5.96×10^{27}g

Body	Radius (Earth=1)	Mass (Earth=1)	Escape velocity, km/sec
Sun	109.1	322.100	623
Mercury	0.39	0.044	3.8
Venus	0.97	0.82	10.4
Earth	1.00	1.00	11.2
Moon	0.27	0.0123	2.4
Mars	0.53	0.108	5.1
Jupiter	10.95	317.1	60.1
Saturn	9.02	94.9	36.6
Uranus	4.00	14.65	21.6
Neptune	3.92	17.16	23.9

B. DYNAMICS

FUNDAMENTAL CONCEPTS AND LAWS

Dynamics deals with the laws of motion of bodies and with the factors which cause or change this motion. Any change in the motion or shape of a body is a result of the interaction of at least two bodies.

The physical quantity characterising the interaction of bodies is called a *force*; it determines the change of motion, or the change of shape, of a body, or both.

Force is a vector quantity. The addition of two forces simultaneously acting on a body is performed according to the parallelogram (addition of vectors).

1. Laws of Dynamics

Newton's First Law of Motion. Every body continues in a state of rest, or uniform motion in a straight line, unless it is compelled to change that state by the application of some external force.

That property of matter by virtue of which a body tends to retain the magnitude and direction of its velocity unchanged is called *inertia*. The change in the motion of a body depends, in addition to the external force, on the quantity of matter in the body. The greater the quantity of matter in the body, the stronger is the tendency of the body to preserve a constant velocity, the greater is the *inertia* of the body. Thus, the quantity of matter in a body determines the physical property of *inertia*. The measure of inertia is the *mass* of the body. Mass is measured in *kilograms* (kg). 1 kg is the mass of a platinum-iridium standard bar.

Newton's Second Law of Motion. The force acting on a body is equal to the product of the mass of the body and the acceleration produced by this force, and coincides in direction with the acceleration. Thus, Newton's second law of motion gives the relation between the applied force (F), the mass of the body (m) and the resulting acceleration (a):

$$F = ma. \tag{1,13}$$

The motion of a body may be characterised by another quantity, called the *momentum*, $K = mv$. At present the quantity mv is frequently called the *impulse of the body*. If the applied force is constant, then

$$F = \frac{mv_t - mv_0}{t},$$

or

$$Ft = mv_t - mv_0. \tag{1,14}$$

The quantity Ft is called the *impulse*.

The change in momentum is equal to the impulse of the force and takes place in the direction of action of the force. Force is measured in *newtons* (N). 1 N is the force which when acting on a body of 1 kg mass produces an acceleration of 1 m/sec.

Newton's Third Law of Motion. When one body exerts a force on another, the second body exerts a force equal in magnitude and opposite in direction on the first body

$$F_1 = -F_2,$$

or

$$m_1a_1 = -m_2a_2, \tag{1,15}$$

where F_1 is the force acting on the first body, F_2—the force acting on the second body, m_1 and m_2—the masses of the first and second bodies, respectively.

A system of bodies which interact only with other bodies of the same system is called *closed*. In a closed system the momentum remains constant. For example, in a system consisting of two bodies the following relation is satisfied:

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2, \tag{1,16}$$

where v_1 and v_2 are the velocities of the first and second bodies before interaction, and u_1 and u_2—the respective velocities after interaction.

The mass per unit volume of a substance is called *density* (ρ). The concept of specific gravity is frequently used. *Specific gravity* (d) is the ratio of the density of a substance to the density of water:

$$\rho = \frac{m}{V}, \tag{1,17}$$

$$d = \frac{P}{V}, \tag{1,18}$$

where m is the mass of the body, P—its weight, V—its volume.

2. Work, Power and Energy

Work (A) in physics is defined as the product of the force and the distance through which it acts. If the force does not coincide in direction with the distance, then the work equals:

$$A = FS\cos\alpha, \tag{1,19}$$

where α is the angle between the force and the distance through which the body moves.

Power (N) is defined as the work performed in unit time:

$$N = \frac{A}{t}, \tag{1,20a}$$

$$N = Fv. \tag{1,20b}$$

When work is performed in a system of bodies the state of the system changes. The state of the system is characterised by its *energy*. When the state of the system changes work is being performed. If we denote by E_1 and E_2 the initial and final energies of the system, then

$$E_1 - E_2 = A. \tag{1,21}$$

There are two forms of mechanical energy: *kinetic energy* (E_k), or the *energy of motion*, which depends on the relative velocity of the bodies, and *potential energy* (E_p) or the *energy of position*, which depends on the relative position of the bodies.

The kinetic energy of a body equals:

$$E_k = \frac{mv^2}{2}, \tag{1,22}$$

where m is the mass of the body, and v—its velocity.

The *potential energy in the field of gravitation of the earth* is defined as

$$E_p = -\gamma \frac{m_E m}{R}, \qquad (1,23)$$

where γ is the gravitational constant (p. 27), m_E is the mass of the earth, m—the mass of the body, and R—the distance from the centre of the earth to the centre of gravity of the body.

The minus sign in formula (1,23) denotes that when the body is removed to an infinitely great distance (when it is out of the field of gravitation), its potential energy is taken to zero; hence, the energy of bodies situated at a finite distance is negative.

When a body is raised to a small height above the surface of the earth the gravitational field of the earth may be regarded as homogeneous (the acceleration of free fall is constant in magnitude and direction). In a homogeneous field the potential energy of a body equals

$$E_p = mgh, \qquad (1,23a)$$

where m is the mass of the body, g—the acceleration of free fall, h—the height of the body measured from some arbitrary level, at which the value of the potential energy is taken equal to zero. The surface of the earth can serve, for example, as such an arbitrary level.

Work is measured in joules (SI—see page 205).

3. Dynamics of Rotation

Newton's second law for rotational motion takes the form:

$$M = Jj. \qquad (1,24)$$

Here the moment of inertia (J) is analogous to the mass, the torque (M)—to the force, and the angular acceleration (j)—to the linear acceleration.

The *torque* or *moment of force* is defined as the product of the force and the perpendicular distance between the line of action of the force and the axis of rotation.

If two torques are applied to a body, producing rotation in opposite directions, then one of the torques is arbitrarily considered positive, and the other negative.

The *moment of inertia* (or rotary inertia) of a point mass about an axis is equal to the product of the mass and the square of its distance from the axis:

$$J = mR^2. \qquad (1,25)$$

The moment of inertia of a body is the sum of the moments of inertia of the point masses of which the body is composed. The moment of inertia of a body can be expressed in terms of its mass and dimensions.

The moment of inertia of a body about an axis can be determined if we know the moment of inertia of the body about a parallel axis passing through the centre of gravity of the body (see p. 37), the mass of the body m and the distance between the two axes S:

$$J = J_{\text{c.g.}} + mS^2. \tag{1,26}$$

In uniform rotational motion the sum of all the torques is equal to zero.

The uniform motion of a point in a circular path (uniform circular motion) is characterised by centripetal acceleration (which causes the velocity to change in direction) and can take place only if a force acts to produce this acceleration. This force is applied to the point which is describing circular motion and is called the *centripetal force*:

$$F_{\text{c}} = \frac{mv^2}{R}, \tag{1,27a}$$

$$F_{\text{c}} = m\omega^2 R. \tag{1,27b}$$

The centripetal force is directed along the radius towards the axis of rotation and its torque is equal to zero (the perpendicular distance between the force and the axis is zero).

The work done when a constant torque acts through an angle φ in rotational motion equals

$$A = M\varphi. \tag{1,28}$$

The power developed equals

$$N = M\omega. \tag{1,29}$$

The kinetic energy of a rotating body equals

$$E_{\text{k}} = \frac{J\omega^2}{2}. \tag{1,30}$$

4. Friction

When two solid bodies in contact are in motion relative to each other, a force arises which hinders this motion. This force is called *friction*. It is caused by the irregularities of the surfaces in contact, as well as by molecular forces of interaction.

When there is no layer of liquid between the surfaces we speak of *dry friction*.

According to the character of the motion giving rise to dry friction we distinguish *sliding friction* (one body *slides* over the surface of the other) and *rolling friction* (one body *rolls* on the surface of the other).

The magnitude of sliding friction F_{fr} depends on the nature and quality of finish of the surfaces in contact and on the force pressing the surfaces together (the perpendicular force F_p).

$$F_{fr} = kF_p, \tag{1,31}$$

where k is the *coefficient of friction*; k depends on the nature and quality of finish of the surfaces in contact, and to a slight degree on the velocity of motion (the dependence on the velocity is usually neglected). Rolling friction is less than sliding friction. Rolling friction depends on the radius R of the rolling body, on the force pressing the surfaces together and on the quality of the surfaces:

$$F_{fr} = k' \frac{F_p}{R}, \tag{1,32}$$

where k' is a quantity characterising the surfaces in contact; k' has the dimensions of a length. The following are two examples of the value of k' in cm:

A wheel with a steel rim on a steel track 0.05
A cast iron wheel on a steel track 0.12

5. Law of Universal Gravitation

The force of attraction F between two point masses m_1 and m_2 equals:

$$E = \gamma \frac{m_1 m_2}{R^2}, \tag{1,33}$$

where R is the distance between the masses, and γ is the *constant of gravitation*, equal to 6.67×10^{-8} cm^3/g sec^2 (in the CGS system of units*). The constant of gravitation is a quantity equal to the force of attraction between two point masses of unit, mass separated by unit distance. In the case of homogeneous spheres of masses m_1 and m_2 the force of attraction is given by the same formula, except that R now denotes the distance between the centres of the spheres.

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* See p. 205 for the CGS system of units.

The weight P of a body of mass m on the surface of the earth is determined mainly by the force of attraction between the body and the earth:

$$P=\gamma\frac{m_{\mathrm{E}}m}{R_{\mathrm{E}}^2},$$

where m_{E} is the mass of the earth, and R_{E} is the radius of the earth.

In accordance with the law of gravitation, the acceleration of gravity (the intensity of the gravitational field) at a height H above the surface of the earth is given by the formula:

$$g=\gamma\frac{m_{\mathrm{E}}}{(R_{\mathrm{E}}+H)^2},$$

or

$$g=g_0\frac{R_{\mathrm{E}}^2}{(R_{\mathrm{E}}+H)^2}, \qquad (1,34a)$$

where g_0 is the acceleration on the earth's surface.

In the first approximation for $H\ll R_{\mathrm{E}}$

$$g\approx g_0\left(1-2\frac{H}{R_{\mathrm{E}}}\right). \qquad (1,34b)$$

At the centre of the earth the intensity of the gravitational field is equal to zero. If the earth is regarded as a homogeneous sphere then g increases with increasing distance from the centre of the earth. Outside the earth g decreases with increasing distance from the centre of the earth; the dependence of the acceleration g on the distance R from the centre of the earth is depicted in the form of a graph in Fig. 3.

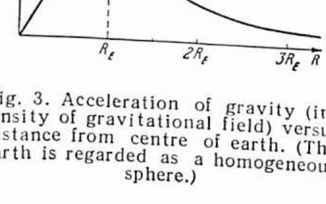

Fig. 3. Acceleration of gravity (intensity of gravitational field) versus distance from centre of earth. (The earth is regarded as a homogeneous sphere.)

TABLES

Table 4

Density of Some Solids (at 20°C)

Substance	Density, g/cm³	Substance	Density, g/cm³
Metals and alloys		*Minerals and rock*	
Aluminium	2.7	Anthracite (dry)	1.2-1.5
Brass	8.4-8.7	Asbestos	0.1-0.5
Bronze	8.7-8.9	Chalk (air dry)	2
Cast iron	7	Corundum	4
Chromium	7.15	Diamond	3.51
Cobalt	8.8	Granite	2.5-3
Constantan	8.88	Marble	2.5-2.8
Copper	8.93	Mica	2.6-3.2
Duralumin	2.79	Quartz	2.65
Germanium	5.3	*Plastics and laminated plastics*	
Gold	19.31	Cellon	1.3
Iron	7.88	Fluoplastic	2.1-2.3
Lead	11.35	Laminated aminoplasts	1.4
Magnesium	1.76	Phenolic plastic, impregnated	1.34-1.4
Manganin	8.5	Plexiglas	1.18
Molybdenum	10.2	Polyacrylate (organic glass)	1.2
Neptunium	19.5	Polystyrene	1.06
Nickel	8.9	Polyvinyl plastic	1.34-1.4
Nickeline	8.77	Teflon	2.2
Platinum	21.46	Textolite	1.3-1.4
Silicon	2.3	Vinyl plastic	1.38-1.40
Silver	10.5	*Different materials*	
Sodium	0.975	Amber	1.1
Steel	7.7-7.9	Bakelite varnish	1.4
Tin	7.29	Beeswax, white	0.95-0.96
Tungsten	19.34	Bone	1.8-2.0
Uranium	19.1	Glass, common	2.5
White babbitt	7.1	Glass, for mirrors	2.55
Zink	7.15	Glass, for thermometers	2.59
Wood (air dry)		Glass, pyrex	2.59
Ash, mahogany	0.6-0.8	Glass, quartz	2.21
Bamboo	0.4	Ice (at 0°C)	0.917
Cedar	0.5-0.6	Porcelain	2.2-2.4
Ebony	1.1-1.3	Rubber, ordinary, hard	1.2
Lignum vitae	1.1-1.4		
Oak, beech	0.7-0.9		
Pine	0.4-0.5		
Walnut	0.6-0.7		

Table 5

Density of Liquids (at 20° C)

Liquid	Density, g/cm³	Liquid	Density, g/cm³
Acetic acid	1.049	Heptane	0.684
Acetone	0.791	Hexane	0.660
Aniline	1.02	Machine oil	0.9
Benzene	0.879	Mercury	13.55
Benzine	0.68-0.72	Methyl alcohol	0.792
Bromine	3.12	Milk of average fat content	1.03
Bromobenzene	1.495	Nitric acid	1.51
Chloroform	1.489	Nitrobenzene	1.2
Crude oil	0.76-0.85	Nitroglycerine	1.6
Diiodomethane	3.325	Sea water	1.01-1.03
Ethyl alcohol	0.79	Toluene	0.866
Formic acid	1.22	Tribromomethane	2.890
Glycerine	1.26	Vaseline oil	0.8
Heavy water (H_2^2O)	1.1086	Water	0.99823

Table 6

Density of Some Metals in the Liquid State

Substance	Temperature, °C	Density, g/cm³
Aluminium	660	2.380
	900	2.315
	1,100	2.261
Bismuth	300	10.03
	600	9.66
	962	9.20
Gold	1,100	17.24
	1,200	17.12
	1,300	17.00
Lead	400	10.51
	600	10.27
	1,000	9.81
Silver	960.5	9.30
	1,092	9.20
	1,300	9.00
Sodium	100	0.928
	400	0.854
	700	0.780
Tin	409	6.834
	574	6.729
	704	6.640

Table 7

Density of Water at Various Temperatures (g/cm^3)

t, °C	Density	t, °C	Density	t, °C	Density
−10	0.99815	7	0.99993	25	0.99707
−9	0.99843	8	0.99988	26	0.99681
−8	0.99869	10	0.99973	27	0.99652
−7	0.99892	11	0.99963	28	0.99622
−6	0.99912	12	0.99952	29	0.99592
−5	0.99930	13	0.99940	30	0.99561
−4	0.99945	14	0.99927	31	0.99521
−3	0.99958	15	0.99913	32	0.99479
−2	0.99970	16	0.99897	33	0.99436
−1	0.99979	17	0.99880	34	0.99394
0	0.99987	18	0.99862	35	0.99350
1	0.99993	19	0.99843	40	0.99118
2	0.99997	20	0.99823	50	0.98804
3	0.99999	21	0.99802	60	0.98318
4	1.00000	22	0.99780	70	0.97771
5	0.99999	23	0.99757	80	0.97269
6	0.99997	24	0.99732	90	0.96534

Note. The maximum density of water corresponds to the temperature 3.98° C.

Table 8

Density of Mercury at Pressure $p=1$ kg/cm^2 and at Various Temperatures

t, °C	ρ, g/cm^3	t, °C	ρ, g/cm^3	t, °C	ρ, g/cm^3	t, °C	ρ, g/cm^3
0	13.5951	25	13.5335	50	13.4723	75	13.4116
5	13.5827	30	13.5212	55	13.4601	80	13.3995
10	13.5704	35	13.5090	60	13.4480	90	13.3753
15	13.5580	40	13.4967	65	13.4358	100	13.3514
20	13.5457	45	13.4845	70	13.4237	300	12.875

Table 9

Density of Various Gases at 0°C and Saturated Vapours at 760 mm Hg

Substance	Density, g/cm³	Substance	Density, g/cm³
Acetylene	0.001173	Ethyl ether (saturated)	0.00083
Air	0.001293	Helium	0.0001785
Ammonia	0.000771	Hydrogen	0.00008988
Argon	0.001783	Krypton	0.00374
Benzene (saturated)	0.000012	Neon	0.000900
Carbon dioxide	0.001977	Nitrogen	0.001251
Carbon monoxide	0.00125	Oxygen	0.001429
Chlorine	0.00322	Ozone	0.002139
Ethyl alcohol (saturated)	0.000033	Water vapour (saturated)	0.000484

Table 10

Average Density of Various Substances

Substance	Density, kg/m³
Asbestos felt	600
Asbestos paper	850-900
Asphalt	2,120
Beets	650
Broadcloth	250
Clay, 15-20% moisture content by weight	1,600-2,000
Concrete mixed with crushed rock, 8% moisture content by weight	2,000
Concrete dry	1,600
Corn (grain)	750
Cotton wool, air dry	80
Foam concrete	300-1,200
Gravel, air dry	1 840
Hay, fresh-mown	50
Hay, compressed	100
Lime plaster, 6-8% moisture content by weight	1,100
Masonry, red brick	1,600-1,700
" , silicate brick	1,700-1,900
Mipor (microporous rubber)	not more than 20
Peas	700
Potatoes	670
Pressboard (made of reeds)	260-360
Reinforced concrete, 8% moisture content by weight	2,200
Sand	1,200-1,600
Sandstone	2,600
Silk	100
Slag, blast-furnace	600-800
,, ,, furnace	900-1,300
Slag concrete, 13% moisture content by weight	1,500
Snow, fresh-fallen	80-190
Woollen cloth	240
Woollen felt	300

Table 11

Moments of Inertia of Various Homogeneous Bodies

Body	Axis	Moment of inertia J
Thin bar of length l	Perpendicular to bar and passing through its centre	$\frac{ml^2}{12}$
Circular disk or cylinder of radius r	Perpendicular to plane of disk and passing through its centre	$\frac{mr^2}{2}$
Sphere of radius r	Diameter of sphere	$0.4\ mr^2$
Thin cylindrical tube or ring of radius r	Axis of tube	mr^2
Circular cylinder of length l and radius r	Perpendicular to axis of cylinder and passing through its centre	$m\left(\frac{l^2}{12}+\frac{r^2}{4}\right)$
Rectangular parallelepiped of dimensions $2a$, $2b$, $2c$	Axis passing through centre and parallel to side $2a$	$m\,\frac{b^2+c^2}{3}$

Note. The table gives the moments of inertia of bodies about axes which pass through their centres of gravity. The moment of inertia about an arbitrary axis can be found according to formula (1,26). For example, the moment of inertia of a thin bar about an axis perpendicular to the bar and passing through one of its ends is:

$$J=\frac{ml^2}{12}+m\left(\frac{l}{2}\right)^2=\frac{ml^2}{3}.$$

Table 12

Coefficients of Sliding Friction for Various Materials

Surfaces in contact	Coefficient of friction
Bronze on bronze	0.2
" steel	0.18
Cast iron on bronze	0.21
" " on cast iron	0.16
Copper on cast iron	0.27
Dry wood on wood	0.25-0.5
Fluoplastic-4 on fluoplastic	0.052-0.086
Fluoplastic on stainless steel	0.064-0.080
Greased leather belt on metal	0.23
Hempen rope, wet, on oak	0.33
" " dry, on oak	0.53
Ice on ice	0.028
Iron-bound runners on snow and ice	0.02
Leather belt, moist, on metal	0.36
" " on oak	0.27-0.38
" " dry, on metal	0.56
Metal, moist, on oak	0.24-0.26
" dry, on oak	0.5-0.6
Oak on oak, along grain	0.48
" " along grain of one surface and across grain of other	0.34
Rubber (tires) on hard soil	0.4-0.6
" " on cast iron	0.83
Sliding bearing, greased	0.02-0.08
Steel (or cast iron) on ferrodo	0.25.0.45
Steel on iron	0.19
" " ice (skates)	0.02-0.03
" " steel*	0.18
" " cast iron*	0.16
Steel-rimmed wheel on steel track	0.16
Wooden runners on snow and ice	0.035

Note. The asterisk denotes materials used in braking and frictional devices.

Table 13

Intensity of Earth's Gravitational Field (Acceleration of Free Fall) for Different Latitudes at Sea Level

Latitude	Acceleration, cm/sec²	Latitude	Acceleration, cm/sec²
0°	978.030	55°45′ (Moscow)	981.523
10°	978.186	59°57′ (Leningrad)	981.908
20°	978.634	60°	981.914
30°	979.321	70°	982.606
40°	980.166	80°	983.058
50°	981.066	90°	983.216

Table 14

Intensity of Gravitational Field (Acceleration of Free Fall) near the Surface of the Sun and Planets

Body	Acceleration, cm/sec²	Body	Acceleration, cm/sec²
Sun	27,400	Jupiter	2,650
Mercury	392	Saturn	1,176
Venus	882	Uranus	980
Earth	980	Neptune	980
Mars	392	Moon	167

C. STATICS OF SOLID BODIES

FUNDAMENTAL CONCEPTS AND LAWS

Statics deals with the conditions of equilibrium of a body or system of bodies. If a number of forces are acting on a body at rest (in equilibrium), such that the directions of the forces intersect in a single point, then the body will remain at rest (in equilibrium) when the vector sum of these forces is zero. The forces may be displaced along their line of action.

Centre of gravity of a solid body or system of bodies. Every particle of a body is subjected to the pull of gravity. The resultant (sum) of all the forces of gravity acting on the particles of the body is called the *weight* of the body.

The *centre of gravity* is called the point about which the sum of the moments of the forces of gravity acting on all the particles of the body is equal to zero. The weight of the body may be considered concentrated at its centre of gravity.

Types of equilibrium. When a body returns to its original position after being slightly displaced, the equilibrium is said to be *stable*.

When a body tends to move as far as possible from its original position when slightly displaced, the equilibrium is called *unstable*.

A body is in *neutral* equilibrium, if, when slightly displaced, it tends neither to return to its original position nor to move further away from it, in other words, when the new position is also a position of equilibrium.

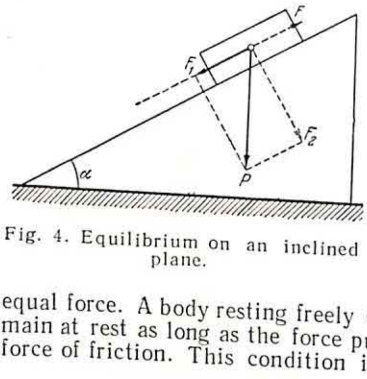

Fig. 4. Equilibrium on an inclined plane.

Conditions of equilibrium of a body on an inclined plane. For a body of weight P to be in equilibrium on an inclined plane which makes an angle α with the horizontal it must be subjected to a force F equal to F_1:

$$F_1 = P\sin\alpha;$$

the force F must be directed upward along the inclined plane (Fig. 4). The body itself presses down on the inclined plane with a force

$$F_2 = P\cos\alpha,$$

while the inclined plane reacts on the body with an equal force. A body resting freely on an inclined plane will remain at rest as long as the force pulling it down is less than the force of friction. This condition is satisfied if

$$\tan\alpha > k,$$

where k is the coefficient of sliding friction.

The lever. A lever is in equilibrium if the sum of the moments of all the forces applied to it equals zero (Figs. 5, *a* and 5, *b*).

$$F_1a - F_2b = 0,$$

where a and b are the lever arms of the applied forces.

The condition that the sum of the moments of all the forces equal zero also applies to the equilibrium of a *windlass* (Fig. 6).

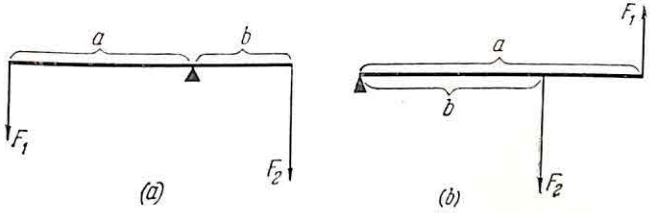

Fig. 5. Levers:
a) Fulcrum between forces acting on lever, *b*) Fulcrum at one end of lever.

Pulleys. The fixed pulley (Fig. 7) serves only to change the direction of the applied force. The movable pulley (Fig. 8) gives us a gain in force. When a movable pulley is at rest or in uniform rotation the sum of all the applied forces and the sum of all the moments is equal to zero.

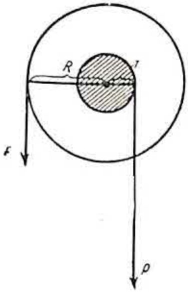

Fig. 6. Schematic diagram of windlass ($F \times R = P \times r$).

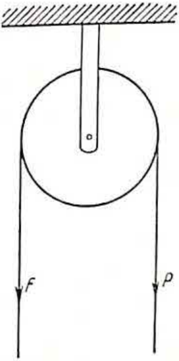

Fig. 7. Schematic diagram of fixed pulley.

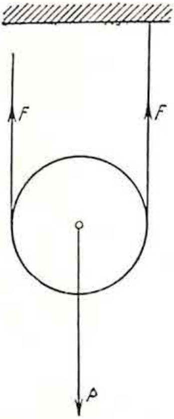

Fig. 8. Schematic diagram of movable pulley.

Hence it follows that

$$P = 2F,$$

or

$$F = \frac{P}{2}.$$

Pulley blocks. A pulley block (Fig. 9) is a combination of fixed and movable pulleys. If the block contains n movable and

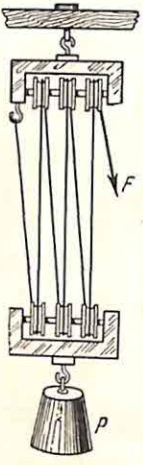

Fig. 9. Pulley block.

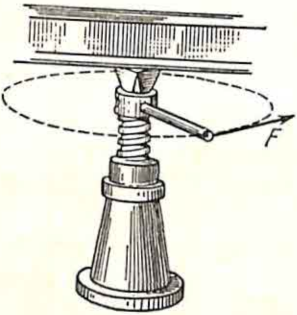

Fig. 10. Jackscrew.

n fixed pulleys, then the force F required to counteract the force P equals

$$F = \frac{P}{2n}.$$

The screw. In the absence of friction the force P acting along the axis of the screw is balanced by a force F applied to the circumference of the screw cap and equal to

$$F = \frac{Ph}{2\pi R},$$

where R is the radius of the screw cap and h—the pitch of the screw (Fig. 10).

TABLES

Table 15

Centres of Gravity of Various Homogeneous Bodies (see Fig. 11)

Body	Position of centre of gravity
Thin bar	At the centre of the bar
Cylinder or prism	In the middle of the straight line connecting the centres of the bases of the cylinder or prism
Sphere	At the centre of the sphere
Flat thin circular segment	On the axis of symmetry at $^{2}/_{5}$ of its height above the base
Pyramid or cone	On the straight line connecting the centre of the base and the apex at $^{1}/_{4}$ the distance from the base
Hemisphere	On the axis of symmetry at $^{3}/_{8}$ the radius from the centre of the sphere
Thin solid triangular plate	At the point of intersection of the medians

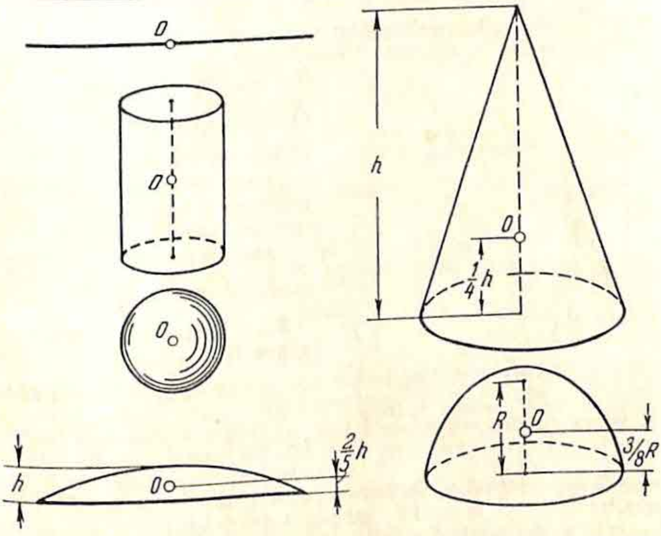

Fig. 11. Position of centre of gravity of some bodies of regular geometrical shape.

D. ELEMENTS OF THE THEORY OF ELASTICITY

FUNDAMENTAL CONCEPTS AND LAWS

Under the action of external forces a solid body undergoes a change in shape, or is deformed. If, when the forces are removed, the body resumes its original shape, the deformation is said to be *elastic*.

When a body undergoes elastic deformation internal elastic forces (restoring forces) arise which tend to restore the body to its original shape. The magnitude of these forces is proportional to the deformation.

Deformation by tension and by compression. The increase in length (Δl) of a body produced by an external force (F) is proportional to the magnitude of the force and to the original length (l), and is inversely proportional to the cross-sectional area (S):

$$\Delta l = \frac{1}{E} \times \frac{lF}{S}, \qquad (1,35a)$$

where $\frac{1}{E}$ is a coefficient of proportionality. Formula (1,35a) is the mathematical expression of *Hooke's law*.

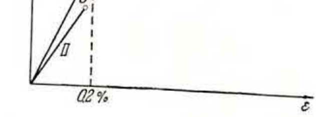

Fig. 12. Stress versus longitudinal strain. Curve *I* – plastic material, curve *II* – brittle material. At point *O* fracture occurs.

The quantity E is called *Young's modulus*, and characterises the elastic properties of the material. The ratio $\frac{E}{S} = p$ is called the *stress*.

The deformation of rods of arbitrary length and cross-sectional area is described by a quantity called the *longitudinal strain* $\varepsilon = \frac{\Delta l}{l}$.

For bodies of arbitrary shape Hooke's law is:

$$p = E\varepsilon. \qquad (1,35b)$$

Young's modulus is numerically equal to the stress required to double the length of a body. Actually, however, rupture occurs at considerably smaller stresses. Fig. 12 represents in graph form the experimentally determined relation between p and ε, where p_{ult} is the *ultimate stress* or *breaking stress*—the stress under which a constriction arises on the rod, p_y is the *yield point*—the stress under which the material begins to flow (the deformation increases without any increase in the applied force), p_{el} is the *elastic limit*, i. e., the stress below which Hooke's law is valid.*

Materials are classified as *brittle* and *plastic*. Brittle materials are destroyed when very small strains are produced in them. Brittle materials can usually withstand greater compression than tension.

Tensile strain is accompanied by a decrease in the diameter of the specimen. If Δd is the change in the diameter, then $\varepsilon_1 = \frac{\Delta d}{d}$ is called the *transverse strain* (transverse contraction per unit dimension). Experience shows that $\left|\frac{\varepsilon_1}{\varepsilon}\right| < 1$.

The absolute value of $\mu = \left|\frac{\varepsilon_1}{\varepsilon}\right|$ is called *Poisson's ratio.*

Shear. *Shear* is called a deformation in which all the layers of a body parallel to a given plane are displaced relative to one another. In deformation by shear the volume of the body remains unchanged. The line segment AA_1 (Fig. 13) equal to the displacement of one plane relative to another, is called the *absolute shear.*

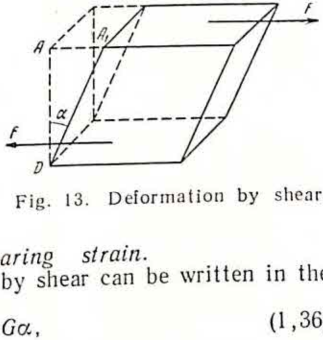

Fig. 13. Deformation by shear.

For small angles of shear the angle $\alpha \cong \tan\alpha = \frac{AA_1}{AD}$ characterises the relative deformation and is called the *shearing strain.*

Hooke's law for deformation by shear can be written in the form:

$$p = G\alpha, \tag{1,36}$$

where the coefficient G is called the *shear modulus.*

Compressibility of matter. When a body is subjected to pressure in all directions its volume decreases by ΔV; as a result elastic forces arise which tend to restore the body to its original volume. The *compressibility* (β) is defined as the relative change in the volume of a body $\frac{\Delta V}{V}$ produced by unit change in the stress (P) acting perpendicular to its surface.

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* It is assumed that the force is applied for a brief time.

The reciprocal of the compressibility is called the *modulus of volume elasticity* or *bulk modulus* (K).

The change in the volume of a body ΔV produced by an increase in pressure ΔP can be computed by the formula:

$$\Delta V = -V\beta\Delta P, \qquad (1,37)$$

where V is the original volume.

The *potential energy of elastic deformation* is given by the formula:

$$E_{\text{pot}} = \frac{F\,\Delta l}{2}, \qquad (1,38)$$

where F is the elastic force, and Δl—the deformation.

TABLES

Table 16

Breaking Stress of Various Materials (kg/mm²)

Material	Breaking stress	
	in tension	in compression
Aminoplasts, laminated	8	20
Bakelite	2-3	8-10
Brass, bronze	22-50	—
Brick	—	0.74-3
Cast iron, white	—	up to 175
„ „ gray, fine-grained	21-25	up to 140
„ „ gray, ordinary	14-18	60-100
Cellon	4	16
Celluloid	5-7	—
Concrete	—	0.5-3.5
Foam plastic in slabs	0.06	—
Getinax (laminated insulation)	15-17	15-18
Granite	0.3	12-26
Ice (0° C)	0.1	0.1-0.2
Oak (15% moisture content) across grain	—	1.5
Oak (15% moisture content) along grain	9.5	5
Phenolic plastic, impregnated	8-10	10-26
Pine (15% moisture content) across grain	—	0.5
Pine (15% moisture content) along grain	8	4
Polyacrylate (organic glass)	5	7
Polystyrene	4	10
Steel, structural	38-42	—
„ silicon-chromium-manganese	155	—
„ carbon	32-80	—
Steel for tracks	70-80	—
Fluoroplast-4	2	—
Textolite ПТК	10	15-25
Vinyl plastic	4	8

Table 17

Moduli of Elasticity and Poisson's Ratios

Material	Young's modulus, kg/mm²	Shear modulus, kg/mm²	Poisson's ratio
Aluminium bronze, casting	10,500	4,200	—
Aluminium, rolled	6,900	2,600-2,700	0.32-0.36
Aluminium wire, drawn	7,000	—	—
Bakelite	200-300	—	—
Brass, rolled, for shipbuilding	10,000	—	0.36
" cold-drawn	9,100-9,900	3,500-3,700	0.32-0.42
Cast iron, wrought	15,500	—	—
Cast iron, white, gray	11,500-16,000	4,500	0.23-0.27
Celluloid	1.74-1.93	—	0.39
Constantan	16,600	6,200	0.33
Copper, casting	8,400	—	—
Copper, cold-drawn	13,000	4,900	—
Copper, rolled	11,000	4,000	0.31-0.34
Duralumin, rolled	7,100	2,700	—
Getinax (laminated insulation)	1,000-1,700	—	—
Glass	5,000-8,000	1,800-3,000	0.2-0.3
Granite	4,900	—	—
Ice	1,000	280-300	—
Invar	14,000	5,600	—
Lead	1,700	700	0.42
Limestone	4,200	—	—
Manganin	12,600	4,700	0.33
Marble	5,600	—	—
Phosphor bronze, rolled	11,500	4,200	0.32-0.35
Plexiglas	535	151	0.35
Rubber	0.8	—	0.47
Steel, alloyed	21,000	8,100	0.25-0.30
" carbon	20,000-21,000	8,100	0.24-0.28
Steel casting	17,500	—	—
Textolite	600-1,000	—	—
Vinyl plastic	300	—	—
Wood	400-1,800	—	—
Zinc, rolled	8,400	3,200	0.27

Table 18

Compressibility of Some Liquids at Different Temperatures

Substance	Temperature, °C	Pressure range, atm	Compressibility, $\beta \times 10^6$ atm^{-1}
Acetic acid	25	92.5	81.4
Acetone	14.2	9-36	111
	0	100-500	82
	0	500-1,000	59
	0	1,000-1,500	47
	0	1,500-2,000	40
Benzene	16	8-37	90
	20	99-296	78.7
	20	296-494	67.5
Castor oil	14.8	1-10	47.2
Ethyl alcohol	20	1-50	112
	20	50-100	102
	20	100-200	95
	20	200-300	86
	20	300-400	80
	100	900-1,000	73
Glycerine	14.8	1-10	22.1
Kerosene	1	1-15	67.91
	16.1	1-15	76.77
	35.1	1-15	82.83
	52.2	1-15	92.21
	72.1	1-15	100.16
	94	1-15	108.8
Mercury	20	1-10	3.91
Nitrobenzene	25	192	43.0
Olive oil	20.5	1-10	63.3
	14.8	1-10	56.3
Paraffin (melting point, 35° C)	64	20-100	83
	100	20-400	24
	185	20-400	137
Sulfuric acid	0	1-16	302.5
Toluene	10	1-5.25	79
	20	1-2	91.5
Water	20	1-2	46
Xylene	10	1-5.25	74
	100	1-5.25	132

Table 19

Allowed Stress of Various Materials (kg/mm ^{2})

Material	Allowed Stress	
	in tension	in compression
Aluminium	3-8	3-8
Brick masonry	0.2	0.06-0.25
Cast iron, gray	2.8-8	12-15
Concrete	0.01-0.07	0.1-0.9
Copper	3-12	3-12
Oak, across grain	—	0.2-3.5
Oak, along grain	0.9-1.3	1.3-1.5
Pine, across grain	—	0.15-0.2
Pine, along grain	0.7-1	1-1.2
Steel, alloyed, for machine-building	10-40 and more	10-40 and more
Steel (grade 3)	14	14
Steel, carbon, for machine-building	16-25	16-25
Stone masonry	Up to 0.03	0.04-0.4

E. MECHANICS OF LIQUIDS AND GASES

FUNDAMENTAL CONCEPTS AND LAWS

Liquids and gases, as distinct from solids, offer no resistance to a change in shape which does not entail a change in volume. To change the volume of a liquid or reduce the volume of a gas one must apply external forces. This property of fluids is called *bulk elasticity*.

Pressure (p) is defined as the perpendicular force acting on unit surface.

1. Statics

External pressure applied to a confined gas or liquid is transmitted equally in all directions (*Pascal's principle*).

A column of liquid or gas in a uniform gravitational field exerts a pressure caused by the weight of the column. If the liquid or gas is assumed to be incompressible, then the pressure

$$p=\rho g h, \qquad (1,39)$$

where ρ is the density of the liquid or gas, g is the acceleration of gravity, and h is the height of the column. The magnitude of the pressure is independent of the shape of the column and depends only on its height.

The heights of columns of liquids in communicating vessels are inversely proportional to their densities:

$$\frac{h_1}{h_2}=\frac{\rho_2}{\rho_1}. \qquad (1,40)$$

A body immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced (*Archimedes' principle*).

2. Dynamics

When a fluid is in motion with a velocity much smaller than the velocity of sound in that fluid, it may be regarded as incompressible. The motion of fluids gives rise to forces of friction. If these forces are small they may be neglected, and the liquid or gas is called an *ideal fluid*.

Motion of an ideal fluid. A liquid or gas is said to flow at a *steady* rate when the velocity and the pressure remain constant at each point in the stream.

In this case an equal volume of fluid flows through any cross-section of the pipe:

$$S_1 v_1 = S_2 v_2, \qquad (1,41)$$

where S_1 and S_2 are the areas of two different cross-sections of the pipe, and v_1 and v_2 are the velocities of the fluid in these cross-sections. When the cross-sectional area of the pipe changes, both the velocity and the pressure of the fluid change in such manner that in any cross-section (for steady flow of an ideal fluid) the following condition is satisfied

$$\left.\begin{aligned} &p+\rho gh+\frac{\rho v^2}{2}=\text{const}\\ \text{or}\quad &p_1+\rho gh_1+\frac{\rho v_1^2}{2}=p_2+\rho gh_2+\frac{\rho v_2^2}{2},\end{aligned}\right\} \qquad (1,42)$$

where p is the pressure, ρ is the density of the fluid, h is the height of the given cross-section of the pipe above a given level, and v is the velocity of the fluid in the given section of the pipe (Fig. 14).

Equation (1,42) is called *Bernoulli's equation*. From this equation follows *Torricelli's theorem*:

$$v = \sqrt{2gH}, \tag{1,43}$$

where v is the velocity of the liquid emerging from a small orifice in the vessel, and H is the height of the surface of the liquid above the orifice (Fig. 15).

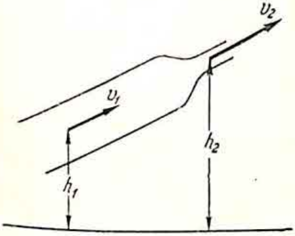

Fig. 14. Illustration to formula (1,42).

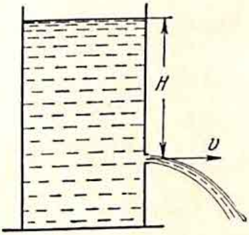

Fig. 15. Flow of liquid from a small orifice.

Motion of a viscous fluid. When one layer of a fluid moves over another layer forces of friction arise.

When a solid (e. g., a sphere) moves through a fluid, the adjacent layer of fluid adheres to the surface of the solid and moves with it, while the remaining layers of fluid slide over one another. The force acting on a solid moving in a viscous medium (fluid) is opposite in direction to the velocity and is called the *resistance of the medium*. If no eddies are formed in the wake of the moving body, then the resistance of the medium is proportional to the velocity v. In the particular case of a sphere of radius R the resistance of the medium is

$$F = 6\pi\eta R v, \tag{1,44}$$

where η is the *coefficient of internal friction*, or the *coefficient of viscosity*. In the CGS system of units viscosity is measured in *poises*: 1 poise=1 gm/cm sec.

Formula (1,44) is called *Stokes' formula*.

When a small sphere falls through a viscous fluid its velocity of uniform (steady) motion is determined by the formula

$$v = \frac{g\,\rho-\rho_1}{\eta} \times \frac{2R^2}{9}, \tag{1,45}$$

where ρ is the density of the sphere, R is its radius, ρ_1 is the density of the fluid, η is its viscosity, and g is the acceleration of free fall.

The volume of fluid which flows in unit time through a capillary tube of radius R and length l when the pressure difference on the ends of the tube is p_1-p_2 equals

$$V=\frac{1}{\eta}\times\frac{\pi R^4}{8l}(p_1-p_2). \qquad (1,46)$$

The viscosity of fluids depends markedly on the temperature.

TABLES

Table 20

Viscosity of Various Liquids at 18° C

Liquid	$\eta \times 10^2$ g/cm sec	Liquid	$\eta \times 10^2$ g/cm sec
Acetic acid	1.27	Glycerine	1,393
Acetone	0.337	Machine oil, heavy	660
Aniline	4.6	Machine oil, light	113
Benzene	0.673	Mercury	1.59
Bromine	1.02	Methyl alcohol	0.632
Carbon disulfide	0.382	Olive oil	90
Castor oil	1,200	Pentane	0.244
Chloroform	0.579	Propyl alcohol	2.39
Cylinder oil, dark	240	Soya bean oil (30° C)	40.6
Cylinder oil, refined (40° C)	1.09	Toluene	0.613
Ethyl alcohol	1.22	Water	1.05
Ethyl ether	0.238	Xylene	0.647

Table 21

Viscosity of Various Gases at 0° C

Gas	$\eta \times 10^4$ g/cm sec	Gas	$\eta \times 10^4$ g/cm sec
Air (without CO_2)	1.72	Hydrogen	0.84
Ammonia	0.93	Methane	1.04
Carbon dioxide	1.40	Nitric oxide	1.72
Carbon monoxide	1.67	Nitrogen	1.67
Chlorine	1.29	Nitrous oxide	1.38
Helium	1.89	Oxygen	1.92

Table 22

Viscosity of Water at Different Temperatures

t, °C	0	5	10	15	20	25	30	40	50
$\eta \times 10^5$ g/cm sec	1.797	1,518	1,307	1,140	1,004	895	803	655	551

t, °C	60	70	80	90	100	110	120	130	140	150	160
$\eta \times 10^5$ g/cm sec	470	407	357	317	284	256	232	212	196	184	174

Table 23

Viscosity of Glycerine, Castor Oil and Benzene at Different Temperatures ($\eta \times 10^2$ g/cm sec)

t, °C / Liquid	0	10	20	30	50	70	100	200
Benzene	—	0.76	0.65	0.56	0.436	0.350	0.261	0.111
Castor oil	—	2,440	987	455	129	49	—	—
Glycerine	12,100	3,950	1,480	600	180	59	13	0.22

Table 24

Viscosity of Liquid Helium

T, °K	4.021	3.738	2.315	2.174	2.145	1.988	1.762	1.304
$\eta \times 10^5$ g/cm sec	2.98	2.75	1.97	1.95	1.55	0.960	0.356	0.124

Table 25

Viscosity of Air at Different Temperatures and Pressures
($\eta \times 10^7$ g/cm sec)

t, °C / p, atm	0	25	100	t, °C / p, atm	0	25	100
1	1,720	1,837	2,180	100	1,970	2,060	2,335
20	1,753	1,865	2,202	200	2,370	2,395	2,530
50	1,815	1,922	2,240	300	2,860	2,800	2,810

Table 26

Viscosity of Some Metals in the Liquid State

Metal	t, °C	$\eta \times 10^6$ g/cm sec
Aluminium	700	2.90
	800	1.40
Bismuth	304	1.65
	451	1.28
	600	0.99
Lead	441	2.11
	551	1.69
	844	1.18
Mercury	20	1.54
	50	1.40
	100	1.24
	200	1.03
	300	0.90
	400	0.83
	500	0.77
	600	0.74
Sodium	103.7	0.69
	400	0.25
	700	0.18
Tin	240	1.91
	400	1.38
	600	1.05

CHAPTER II

HEAT AND MOLECULAR PHYSICS

FUNDAMENTAL CONCEPTS AND LAWS

The thermal state of a body is characterised by a quantity called the *temperature*. A change in the temperature of a body entails a change in almost all its properties (dimensions, density, elasticity, electrical conductivity, etc.).

The temperature of a body is related to the average kinetic energy of thermal motion of its molecules.

Temperature is expressed in different temperature scales. The most widely used is the centigrade (or Celsius) scale. The zero point of the centigrade scale is the point at which water is in equilibrium with ice; the point 100° on the centigrade scale is the boiling point of water at standard atmospheric pressure. In addition to the centigrade scale the Kelvin (or absolute) scale is frequently used; the zero of this scale is at —273.16° C, and the degrees are of the same size as on the centigrade scale. The Réaumur and Fahrenheit scales are less frequently used.

Fig. 16 shows the centigrade, Réaumur and Fahrenheit scales for comparison.

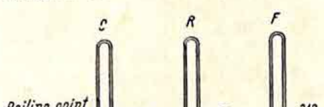

Fig. 16. Centigrade, Réaumur and Fahrenheit thermometer scales.

1. Calorimetry

When a body is heated its internal energy is increased. Thus, heat can be measured in units of work or energy. Historically, however, a special unit—the *calorie*—was adopted for measuring heat.

The *calorie* is defined as the quantity of heat required to raise the temperature of one gram of water one degree—from 19.5° C to 20.5° C.

The *kilocalorie* (or kilogram calorie) $=1{,}000$ cal $=427$ kgm $=$ $=0.24$ joule.

The quantity of heat required to raise the temperature of a body of unit mass from t_0 to $t_1 = t_0 + \Delta t$ is denoted by ΔQ. The *mean specific heat* in the given temperature interval $(t_1 - t_0)$ is defined as the ratio $\frac{\Delta Q}{\Delta t}$. The limit of this ratio

$$c_{t_0} = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t}$$

s, by definition, the *true specific heat* at the temperature t_0. The true specific heat depends on the temperature. However, in most cases this dependence is neglected and it is assumed that the true specific heat (or, simply, the *specific heat*) can be defined as the quantity of heat required to raise the temperature of a body of unit mass from t° C to $(t+1)$° C at any temperature t.

The quantity of heat Q absorbed by a body of mass m when its temperature is increased by Δt equals

$$Q = cm\Delta t, \qquad (2,1)$$

where c is the specific heat. The specific heat of a body also depends on the conditions under which it is heated. If the body is heated at constant pressure then c_p is defined as the *specific heat at constant pressure*. If the volume of the body does not change upon heating, then c_v is defined as the *specific heat at constant volume*. When a body is heated under constant pressure, a part of the heat imparted to it is spent on the work of expansion of the body; hence, $c_p > c_v$. The specific heats c_p and c_v for a substance in the solid state differ very little.

For a given pressure there exists for every substance a definite temperature, called the *melting point*, at which the substance passes from the solid to the liquid state. Throughout this transition the temperature remains constant. Upon melting a substance increases in volume (except for ice, cast iron and bismuth which decrease in volume). The quantity of heat required to melt a body is given by the formula

$$Q = \lambda m, \qquad (2,2)$$

where m is the mass of the molten body, and λ is the heat of fusion.

The *heat of fusion* is defined as the quantity of heat required to convert unit mass of a solid at the melting point into liquid at the same temperature. When a liquid crystallises (solidifies), heat is evolved.

The heat of fusion is equal to the heat of crystallisation *.

When a liquid is contained in an open vessel vaporisation— conversion from the liquid to the gaseous state—takes place continually on its surface. During vaporisation molecules escape from the surface of the liquid. Vaporisation which takes place not only on the surface, but within the liquid as well, is called *boiling*. A liquid boils at a definite (for a given external pressure) temperature. This temperature is called the *boiling point*. It remains constant throughout the process of boiling. Boiling requires the expenditure of a quantity of heat:

$$Q = rm, \qquad (2,3)$$

where m is the mass of evaporated liquid and r is the heat of vaporisation.

The *heat of vaporisation* is defined as the quantity of heat required to convert unit mass of a liquid at the boiling point into vapour at the same temperature. When a vapour or gas is condensed (i. e., converted from the gaseous to the liquid state) heat is evolved.

The heat of vaporisation is equal to the heat of condensation.

The boiling point and the melting point depend on the external pressure.

The evaporation of a liquid from an open vessel can proceed until all of the liquid is converted into vapour. In a closed vessel evaporation proceeds until a state of equilibrium between the mass of the liquid and that of the vapour is reached. At this stage evaporation and condensation compensate each other. Such a state of equilibrium is called *dynamic*. A vapour which is in dynamic equilibrium with its liquid is called a *saturated* vapour. The pressure and density of a saturated vapour are determined by the temperature.

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* This refers to crystalline and polycrystalline bodies. A *crystalline* body is one whose properties are different in different directions. A body composed of numerous crystals is called *polycrystalline*.

Boiling occurs at the temperature at which the pressure of the saturated vapour is equal to the external pressure.

The pressure and density of a saturated vapour increase, while the density of the liquid decreases with increasing temperature. When a liquid is heated in a closed vessel the result will depend on the amount of liquid. If the quantity of liquid is great, then upon expansion it will eventually occupy the entire volume of the vessel. If the quantity of liquid is small, then at a certain temperature it will evaporate completely. For a certain initial quantity of liquid in the vessel the liquid and its saturated vapour will remain in equilibrium as the temperature increases, up to a certain point, at which their densities become equal and the meniscus dividing them disappears. This state is called the *critical* state, and the values of the density, pressure and temperature corresponding to it are called *critical* values.

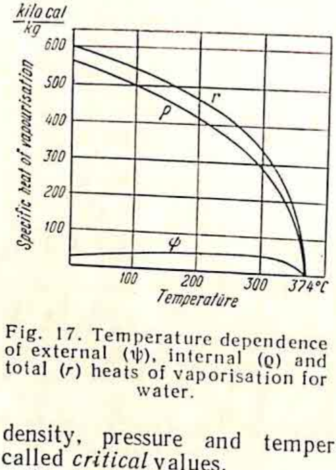

Fig. 17. Temperature dependence of external (ψ), internal (ϱ) and total (r) heats of vaporisation for water.

The heat of vaporisation depends on the temperature. As the temperature increases the heat of vaporisation decreases, and at the critical temperature it becomes zero. The heat of vaporisation (r) is expended on the work performed by the molecules in escaping through the surface layer of the liquid (internal heat of vaporisation ρ), and the work of expansion upon passing from the liquid to the vapour state (external heat of vaporisation Ψ). Fig. 17 shows the dependence of r, ρ, and Ψ on the temperature t for water.

2. Thermal Expansion of Solids and Liquids

A change in the temperature of solids and liquids is accompanied by a change in their linear dimensions and volume. The length of a solid body at a temperature $t°$ C (l_t) is determined by its length at 0° C (l_0), the temperature (t) and the coefficient of linear expansion (α):

$$l_t = l_0(1+\alpha t). \tag{2,4}$$

The *coefficient of linear expansion* is defined as the mean (for the temperature interval from 0° C to $t°$ C) increase in unit length of a body for one degree rise in temperature

$$\left(\alpha = \frac{l}{l_0} \times \frac{l_t - l_0}{t}\right).$$

Similarly, for the volume of a body

$$v_t = v_0(1+\beta t), \tag{2,5}$$

where β is the coefficient of volume expansion.

The *coefficient of volume expansion* is defined as the mean (for a given temperature interval) increase in unit volume of a body for one degree rise in temperature $\left(\beta = \frac{1}{v_0} \times \frac{v_t - v_0}{t}\right)$.

For an isotropic solid (a body whose properties are the same in every direction) $\beta = 3\alpha$.

The coefficients of volume and linear expansion are expressed in 1/degree.

The following formulas are more exact:

$$\Delta l = l_0(at+bt^2), \quad l_t = l_0(1+at+bt^2). \tag{2,6}$$

Thus, the coefficient of linear expansion varies with the temperature range in which the body is heated.

For example, for iron $l_t = l_0(1+117\times10^{-7}t+4.7\times10^{-9}t^2)$, and the coefficient of linear expansion of iron upon heating from 0° C to 75° C equals 1.21×10^{-5} 1/degree, while for the temperature range 0° C-750° C it equals 1.52×10^{-5} 1/degree.

When a body is heated its density changes. The density of a body at a temperature t is given by the formula

$$\rho_t = \frac{\rho_0}{1+\beta t}, \tag{2,7}$$

where ρ_0 is the density of the body at 0° C, and β is the coefficient of volume expansion.

3. Transfer of Heat

Heat can be transmitted by convection, conduction and radiation (see thermal radiation).

Convection. In fluids temperature differences are evened out mainly by *convection*, by the flow of the fluid from a warmer to a colder region. Convection does not take place in solids.

Conduction. *Conduction* is the transfer of heat brought about by the random motions of atoms or molecules.

The quantity of heat transferred through a layer of substance of thickness l and cross-sectional area S having a temperature difference T_2-T_1 on its planes in a time t is given by

$$Q=\lambda\,\frac{T_2-T_1}{l}\,St, \tag{2,8}$$

where λ is the thermal conductivity.

The *thermal conductivity* is defined as the quantity of heat transferred in unit time through a layer of unit thickness and unit cross-sectional area when the temperature difference between the two surfaces of the layer is 1°.

The thermal conductivity is usually expressed in $\frac{\text{kilocal}}{\text{m hour degree}}$ or $\frac{\text{cal}}{\text{cm sec degree}}$. In the first case, the quantity of heat transferred is expressed in kilocalories when the thickness of the layer is expressed in m, the cross-sectional area in square meters and the time in hours.

4. Surface Tension of Liquids

The molecules in the surface of a liquid experience forces of attraction due to the remaining molecules, which tend to pull them into the liquid.

The surface layer of molecules is in a state resembling that of an elastic membrane under tension which tends to contract. Every section of the surface experiences the pull of all the surrounding sections which keep it in a state of tension. These forces are directed along the surface layer and are called *forces of surface tension*.

The force of surface tension is given by the formula

$$F=\alpha l, \tag{2,9}$$

where l is the perimeter of the surface layer of liquid and α is the coefficient of surface tension.

The *coefficient of surface tension* (or, simply, the *surface tension*) is defined as the force acting on unit length of a rectilinear boundary of the surface layer of a liquid.

The surface tension decreases with increasing temperature and vanishes at the critical temperature.

5. Gas Laws

The behaviour of most substances in the gaseous state under ordinary conditions is described by the equation

$$pv = \frac{m}{\mu} RT. \tag{2,10}$$

This equation is called the *equation of state of an ideal gas* or the general gas law (*Clapeyron-Mendeleyev's equation*). Here p is the pressure of the gas, v — the volume occupied by m grams of the gas, μ — a mole (a *mole* or *gram molecular weight* of any substance is an amount of that substance whose mass, expressed in grams, is numerically equal to the molecular weight), R— the universal gas constant, T — the temperature on the Kelvin scale. This equation is valid (in the first approximation) for all substances in the gaseous state, if the density is much less than the density of the same substance in the liquid state.

The number of molecules contained in one mole is the same for all substances and is called *Avogadro's number* (N); $N = 6.02 \times 10^{23}$ mole^{-1}.

From equation (2,10) we deduce Gay-Lussac's law, Charles' law and Boyle's law. For constant p and m (since R=const and μ is constant for the given substance)

$$v_1 = v_0 \frac{T_1}{T_0},$$

where v_0 and T_0 are the volume and temperature of the gas at 0° C. Whence follows Gay-Lussac's law (the equation of an *isobaric process*):

$$v = v_0 \left(1 + \frac{1}{273} t\right). \tag{2,11a}$$

For constant v and m we obtain Charles' law (*isochoric process*):

$$p = p_0\left(1 + \frac{1}{273}\,t\right). \tag{2,11b}$$

For constant T and m (isothermal process) we obtain Boyle's law:

$$p_1 v_1 = p_2 v_2. \tag{2,11c}$$

The quantity 1/273.16 degree^{-1}* is called the *coefficient of volume expansion at constant pressure* or the *coefficient of pressure change at constant volume* of an ideal gas. For real gases at pressures close to atmospheric or greater, the respective coefficients differ somewhat from this value.

The density of a gas ρ may be computed from equation (2,10) if the pressure p, the temperature T and the molecular weight of the gas are known:

$$\rho = \frac{m}{v} = \frac{\mu p}{RT}. \tag{2,12}$$

When a gas expands isothermally (at constant temperature) it performs work against the external pressure. This work is performed mainly at the expense of the heat absorbed from the surrounding medium. The temperature of the gas and the surrounding medium remain constant. When the gas is compressed it releases heat which goes off into the surrounding medium.

When the volume of a given mass of gas changes without heat entering or leaving the system (*adiabatic process*) the relation between the pressure and the volume is expressed by the equation of the adiabat:

$$pv^{\gamma} = \text{const}, \tag{2,13}$$

where $\gamma = \frac{c_p}{c_v}$.

6. Fundamentals of the Kinetic Theory of Gases

From the molecular point of view a gas consists of a huge number of freely moving particles (molecules or atoms). These particles are in constant motion with different velocities which change when the particles collide.

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* $1/273.16 = 3.661 \times 10^{-3}$.

The pressure of a gas is due to the impact of individual molecules on the walls of the container. It is equal to

$$p=\frac{1}{3}\,nmc^2, \tag{2,14a}$$

or

$$p=nkT, \tag{2,14b}$$

where n is the number of molecules in unit volume, m is the mass of a molecule, $k=\frac{R}{N}$ is called Boltzmann's constant, T is the temperature on the Kelvin scale, and c is the root mean square velocity of the molecules.

The *root mean square velocity* of the molecules is defined as

$$c=\sqrt{\frac{v_1^2+v_2^2+v_3^2+\ldots+v_n^2}{n}}, \tag{2,15}$$

where n is the number of molecules, and v_1 is the velocity of the i-th molecule.

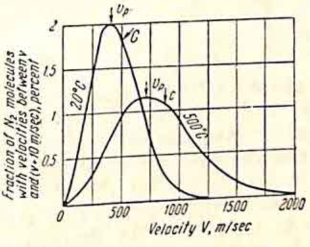

Fig. 18. Distribution of velocities of nitrogen molecules at temperatures 20°C and 500°C. v_p — most probable velocity at given temperature, c — root mean square velocity.

The pressure of a mixture of ideal gases is equal to the sum of the partial pressures of the component gases.

The *partial pressure* is defined as the pressure which each of the gases would exert if it alone occupied the whole volume:

$$p=p_1+p_2\cdots+p_n \tag{2.16}$$

where p_1, p_2, ..., p_n are the partial pressures.

The *average kinetic energy* of translational motion of the molecules depends only on the temperature of the gas:

$$E=\frac{3}{2}\,kT. \tag{2,17}$$

The molecules of a gas move with different velocities. Fig. 18 gives the dependence of the fraction of molecules $\frac{\Delta n}{n}$, with velocities between v and $v+\Delta v$, on the velocity. The velocity corresponding to the maximum of the curve in Fig. 18 is called the *most probable velocity*.

The *average velocity* of the molecules is defined by the relation

$$v_{\mathrm{av}}=\frac{v_1+v_2+v_3+\ldots+v_n}{n}. \qquad (2,18)$$

The average velocity is greater than the most probable velocity and less than the root mean square velocity.

Some molecules, whose velocities are greater than the escape velocity, can escape from the upper layers of the atmosphere into interplanetary space.

The atmosphere is a mixture of gases held by the field of gravity of the planet which it surrounds. The pressure of the atmosphere decreases with increasing distance (h) from the surface of the planet. If it is assumed that the temperature of the atmosphere is independent of the height, then

$$p=p_0e^{-\frac{\mu gh}{RT}}, \qquad (2,19)$$

where μ is the average molecular weight of the mixture of gases comprising the atmosphere, g—the acceleration of free fall near the surface of the planet, R—the universal gas constant, T—the absolute temperature, p_0—the pressure of the atmosphere at the surface of the planet, e—the base of the natural system of logarithms ($e\approx 2.72$). In the case of the earth this formula can be written in the form

$$h=8{,}000\log\frac{p_0}{p}, \qquad (2,19\text{a})$$

where h is the height in metres, $T=273°$ K.

In many countries, including the U.S.S.R., scientific data are often corrected for a *standard atmospheric pressure*, which is taken equal to the pressure at sea level at 15° C when the mercury barometer registers 760 mm and the temperature falls by 6.5° with every 1,000 m increase in elevation.

Table 51 gives the relation between the height, pressure, density and temperature of a standard atmosphere.

The air about us always contains a certain amount of water vapour. The mass of water vapour contained in 1 cubic meter of air is called the *absolute humidity*. The absolute humidity can be measured by the partial pressure of the water vapour.

As the absolute humidity increases, the water vapour approaches the state of saturation. The *maximum absolute humidity** at a given temperature is defined as the mass of saturated water vapour contained in 1 cubic metre of air.

The *relative humidity* is defined as the ratio of the absolute humidity to the maximum absolute humidity at the given temperature, expressed in per cent.

The thermal conductivity of a gas (λ) is calculated by the formula

$$\lambda = \frac{1}{3} \rho v_{av} c_v l, \tag{2,20}$$

where ρ is the density of the gas, v_{av}— the average velocity of the gas molecules, c_v—the specific heat at constant volume, l— the mean free path.

The *mean free path* is defined as the average path which a molecule travels between successive collisions with other molecules. The mean free path in a gas is given by the formula

$$l = \frac{kT}{\sqrt{2}\pi\sigma^2 p}, \tag{2,21}$$

where σ is the diameter of a molecule of the gas.

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* Under certain conditions supersaturation of the vapour can set in.

TABLES

Table 27

Specific Heat, Heat of Fusion, Melting and Boiling Points

Substance	Specific heat at 20° C, cal/g degree	Melting point, °C	Heat of fusion, cal/g	Boiling point, °C
Acetone	0.52	−94.3	—	56.7
Aluminium	0.21	658.7	76.8	2,000
Benzene	0.407	5.5	30.4	80.2
Brass	0.0917	900	—	—
Carbon disulfide	0.24	−112	—	46.2
Cast iron	0.12	1,100-1,200	23-33	—
Copper	0.094	1,083	42	2,300
Ethyl alcohol	0.58	−114	25	78.3
Ethyl ether	0.56	−116.3	27	34.6
Fluoplastic-4	0.25-0.22	—	—	—
Glycerine	0.58	−20	42	290
Gold	0.032	1,063	15.9	2,600
Ice (water)	0.50	0	79.7	100
Iron	0.119	1,530	23-33	3,000
Lead	0.03	327	5.36	—
Mercury	0.033	−38.9	2.8	356.7
Methyl alcohol	0.6	−97	24	64.7
Naphthalene	0.29	80	—	2.18
Nickel	0.11	1,452	58.3-73	—
Propyl alcohol	0.57	−127	20.7	96
Silver	0.056	960.5	21	2,100
Steel	0.11	1,300-1,400	49	—
Tin	0.055	231.9	14	—
Toluene	0.414	−95.1	17.2	110.7
Vinyl plastic	0.271-0.286	—	—	—
Wood:				
oak, 6-8% moisture content by weight	0.57	—	—	—
pine, 8% moisture content by weight	0.65	—	—	—
Wood's alloy	0.04	65.5	8.4	—

Table 28

Change in Volume upon Melting

Substance	Relative change in volume, $\frac{\Delta V}{V}\%$	Substance	Relative change in volume, $\frac{\Delta V}{V}\%$
Aluminium	6.6	Lithium	1.5
Antimony	−0.94	Magnesium	4.2
Bismuth	−3.32	Mercury	3.6
Cadmium	4.74	Potassium	2.41
Cesium	2.6	Silver	4.99
Gold	5.19	Sodium	2.5
Ice (water)	−8.3	Tin	2.6
Indium	2.5	Zinc	6.9
Lead	3.6		

Table 29

Specific Heat* of Various Solids (in cal/g degree) at Different $t°$ C

a) True

Substance	−200°	−100°	0°	100°	200°	300°	500°
Copper	0.040	0.082	0.091	0.094	0.098	0.101	0.107
Silica glass	0.043	0.116	0.167	0.199	—	0.244	0.266
Silver	0.0375	0.052	0.056	0.057	0.060	—	0.063

b) Average

Substance	−100°-0°	0°-100°	0°-200°	0°-300°
Copper	0.087	0.093	0.096	0.097
Silica glass	0.143	0.183	—	0.210
Silver	0.054	0.56	—	0.057

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* The values of the specific heats are expressed in 20-degree calories (the specific heat of water at 20° C is taken equal to unity).

Table 30

Specific Heat c_p of Water (in cal/g degree) at Different t°C.

Temperature	c_p	Temperature	c_p	Temperature	c_p
0°	1.0104	40°	0.9984	70°	1.0014
5°	1.0063	35°	0.9984	75°	1.0020
10°	1.0033	50°	0.9990	80°	1.0027
15°	1.0013	60°	1.0001	90°	1.0041
20°	1.0000	65°	1.0007	100°	1.0056
30°	0.9986				

Table 31

Specific Heat c_p of Liquid Ethyl Alcohol (in cal/g degree) at Different Temperatures and Pressures

Temperature, °C Pressure, g/cm^2	−60	−40	−20	0	20	40	60
10	0.38	0.428	0.476	0.525	0.576	0.626	0.678
60	0.379	0.425	0.472	0.519	0.568	0.617	0.666

Temperature, °C Pressure, kg/cm^2	80	100	120	140	160	180	200
10	0.731	0.784	0.840	0.895	—	—	—
60	0.716	0.767	0.820	0.874	0.930	0.999	1.09

Table 32

Specific Heat of Some Gases at 1 atm (in cal/g degree)

Temperature, °C	Oxygen		Air		Carbon dioxide		Water vapour		Ethyl alcohol	
	c_p	c_p/c_v	c_p	c_p/c_v	c_p	c_p/c_v	c_p	c_p/c_v	c_p	c_p/c_v
0	0.2185	1.397	0.240	1.400	0.1946	1.301	—	—	0.320	1.16
100	0.223	1.385	0.241	1.397	0.2182	1.260	0.502	1.28	0.403	1.12
200	0.230	1.37	0.245	1.390	0.2371	1.235	0.472	1.30	0.480	1.10
300	0.2376	1.353	0.250	1.378	0.2524	1.217	0.481	1.29	0.554	1.08
600	0.2553	1.321	0.266	1.345	0.2847	1.188	0.527	1.26	0.756	1.06

Table 33

Specific Heat c_p of Air at 20 kg/cm^2

Temperature, °C	0	50	100	150	200	250	280
c_p, cal/g degree	0.2492	0.248	0.247	0.2466	0.2463	0.2468	0.2471

Table 34

Specific Heat c_p of Carbon Dioxide at 65 kg/cm^2

Temperature, °C	25	30	50	75	100	125
c_p, cal/g degree . . .	1.375	0.7960	0.4043	0.324	0.291	0.2748

Temperature, °C	150	200	250	300	600
c_p, cal/g degree . . .	0.2679	0.2622	0.2628	0.2656	0.2889

Table 35

Heat of Vaporisation at Boiling Point and Standard Atmospheric Pressure

Substance	Heat of vaporisation, cal/g	Substance	Heat of vaporisation, cal/g
Acetone	125	Liquid hydrogen	108
Benzene	94	Liquid nitrogen	47.6
Benzine, aviation grade	55-75	Liquid oxygen	50.9
Carbon disulfide	85	Mercury	68
Ethyl alcohol	202	Methyl alcohol	265
Ethyl ether	83.8	Propyl alcohol	163
Kerosene	50-55	Toluene	87
Liquid helium	6	Water	539.7

Table 36

Heat of Vaporisation of Carbon Dioxide at Different Temperatures

Temperature, °C	Heat of vaporisation, cal/g	Temperature, °C	Heat of vaporisation, cal/g
−50	80.6	0	56.5
−40	76.5	20	37.0
−30	72.5	30	15.0
−10	62.5	31.1	0.0

Table 37

Equilibrium Densities of Liquid and Vapour. Ethyl Alcohol

Temperature, °C	Pressure, atm	Density of liquid, g/cm³	Density of saturated vapour, g/cm³
78.3	1.00	0.7365	0.00165
90	1.562	0.7251	0.00250
140	7.486	0.6631	0.01152
170	15.61	0.6165	0.02446
190	23.94	0.5782	0.0397
200	29.2	0.5568	0.0508
210	35.31	0.5291	0.0655
220	42.38	0.4958	0.0854
230	50.53	0.4550	0.1135
240	59.92	0.3825	0.1715
243.1	63.1	0.2755	0.2755

Table 38

Equilibrium Densities of Liquid and Vapour. Water

Temperature, °C	Pressure, atm	Density of liquid, g/cm³	Density of saturated vapour, g/cm³
0	0.00623	1.000	0.00000484
50	0.126	0.990	0.0000834
100	1.033	0.963	0.000598
150	4.854	0.914	0.00255
200	15.857	0.865	0.00787
250	40.56	0.799	0.0199
300	87.61	0.714	0.0463
330	131.18	0.641	0.0772
350	168.63	0.574	0.1135
360	190	0.528	0.1442
370	214.68	0.45	0.203
374.15	225.65	0.307	0.307

Table 39

Critical Parameters

Substance	Critical temperature, °C	Critical pressure, atm	Critical density, g/cm³
Acetic acid	321.6	57.2	0.351
Acetone	235	47	0.268
Benzene	288.6	47.7	0.304
Carbon dioxide	31.1	73	0.460
Ethyl alcohol	243.1	63.1	0.276
Helium	−267.9	2.26	0.069
Hydrogen	−239.9	12.8	0.031
Methane	−82.5	45.8	0.162
Methyl alcohol	240	78.7	0.272
Naphthalene	468.2	39.2	—
Nitrogen	−147.1	33.5	0.311
Oxygen	−118.8	49.7	0.430
Propyl alcohol	263.7	49.95	0.273
Toluene	320.6	41.6	0.292
Water	374.15	222	0.307

Table 40

Properties of Saturated Water Vapour

Pressure, kg/cm²	Temperature, °C	Specific volume of vapour, m³/kg	Heat of vaporisation, cal/g
0.02	17.2	68.3	586.9
0.1	45.4	14.96	570.4
0.2	59.7	7.8	563.7
0.4	75.4	4.071	554.6
0.6	85.45	2.785	548.6
0.8	93.0	2.127	544.1
0.9	96.2	1.905	542.0
1	99.1	1.726	540.2
1.0333	100	1.674	539.7
1.23	105	1.42	535.4
1.8	116.3	0.996	529.1
2	119.6	0.902	526.9
3	132.9	0.617	517.7
4	142.9	0.4708	510.4
5	151.1	0.3818	504.1
6	158.1	0.3214	498.7
7	164.2	0.2778	493.7
8	169.6	0.2448	489.2
9	174.5	0.2189	485.0
10	179.0	0.1980	481.1
12	187.1	0.1663	473.8
14	194.1	0.1434	467.2
16	200.4	0.1261	461.2
18	206.2	0.1125	455.5
20	211.4	0.1015	450.3
30	232.8	0.0679	427.5
40	249.2	0.0506	408.9

Table 41

Coefficients of Volume Expansion of Liquids β at about 18°C

Substance	$\beta \times 10^4$ 1/degree	Substance	$\beta \times 10^4$ 1/degree
Acetone	14.3	Methyl alcohol	11.9
Aniline	8.5	Nitric acid	12.4
Benzene.	10.6	Petroleum	9.2
Carbon disulfide . . .	11.9	Propyl alcohol	9.8
Chloroform	12.8	Toluene	10.8
Ethyl alcohol	11.0	Turpentine	9.40
Ethyl ether	16.3	Water at 5°-10° . .	0.53
Formic acid	10.2	" " 10°-20° . .	1.50
Glycerine	5.0	" " 20°-40° . .	3.02
Kerosene	10.0	" " 40°-60° . .	4.58
Mercury	1.81	" " 60°-80° . .	5.87

Table 42

Coefficients of Linear Expansion α of Solids at about 20° C

Substance	$\alpha \times 10^6$	Substance	$\alpha \times 10^6$
Aluminium	22.9	Iron, cast	10.2
Bismuth	13.4	Iron, pig	10.4
Brass	18.9	Iron, wrought	11.9
Brick masonry	5.5	Lead	28.3
Bronze	17.5	Magnesium	25.1
Carbon (graphite)	7.9	Nickel	13.4
Cement and concrete	12.0	Platinum	8.9
Constantan	17.0	Platinum-iridium alloy	8.7
Copper	16.7	Porcelain	3.0
Diamond	0.91	Quartz (fused)	0.5
Duralumin	22.6	Steel 3 (grade 20)	11.9
Ebonite	70	Steel, stainless	11.0
German silver	18.4	Tin	21.4
Glass, ordinary	8.5	Tungsten	4.3
Glass, pyrex	3	Vinyl plastic	70
Gold	14.5	Wood (across grain)	50-60
Granite	8.3	Wood (along grain)	2-6
Ice(from −10°C to 0°C)	50.7	Zinc	30.0
Iridium	6.5		

Table 43

Surface Tension of Liquids at 20° C

Substance	Surface tension, dynes/cm	Substance	Surface tension, dynes/cm
Acetic acid	27.8	Methyl alcohol	22.6
Acetone	23.7	Nitrobenzene	43.9
Aniline	42.9	Olive oil	33.06(18°C)
Benzene	29.0	Petroleum	26
Butyric acid	27.2	Propionic acid	27
Castor oil	36.4(18°C)	Propyl alcohol	23.8
Ethyl alcohol	22.8	Toluene	28.5
Glycerine	59.4	Water	72.8
Kerosene	28.9 (0°C)		

Table 44

Surface Tension of Water and Ethyl Alcohol at Different Temperatures (in dynes/cm)

Temperature, °C / Substance	0	30	60	90	120	150
Ethyl alcohol	24.4	21.9	19.2	16.4	13.4	10.1
Water	75.6	71.18	66.18	60.75	54.9	48.63

Temperature, °C / Substance	180	210	240	300	370
Ethyl alcohol	6.7	3.3	0.1	—	—
Water	42.25	35.4	28.57	14.40	0.47

Table 45

Surface Tension of Metals in the Liquid State

Metal	Temperature, °C	Surface tension, dynes/cm
Aluminium	750	520
Bismuth	300	376
	400	370
	500	363
Lead	350	442
	450	438
	500	431
Mercury	20	465
	112	454
	200	436
	300	405
	354	394
Sodium	100	206.4
	250	199.5
Tin	300	526
	400	518
	500	510

Table 46

Thermal Conductivities

Substance	Moisture content, % of weight	Thermal conductivity, kcal/m hr degree
Metals		
Aluminium	—	180
Brass	—	73.5
Cast iron	—	54
Copper	—	335
Gold	—	269
Iron	—	64
Mercury	—	25
Silver	—	360
Steel	—	39
Insulating Materials		
Asbestos cardboard	Air dry	0.135
Asbestos felt	"	0.045-0.08
Asbestos paper	"	0.152-0.115
Foam concrete	"	0.103-0.275
Foam glass	"	0.063-0.092
Foam resin	"	0.037-0.05
Furnace slag	"	0.20-0.32
Mipor (microporous rubber)	"	0.033
Pressboard (made of reeds)	—	0.09
Wool felt	"	0.04
Other Materials		
Bakelite varnish	—	0.25
Brick masonry	air dry	0.58-0.70
Cardboard	"	0.12-0.30
Clay	15-20	0.6-0.8
Concrete, reinforced	8	1.33
Concrete with crushed rock	8	1.1
Corkboard	0	0.036-0.046
Fluoplastic-3	—	0.05
Fluoplastic-4	—	0.2
Glass, ordinary	—	0.64
Granite	—	1.89
Gravel	air dry	0.31
Ice	—	1.9
Leather	air dry	0.12-0.14
Oak, across grain	6-8	0.17-0.18
Oak, along grain	6-8	0.3-0.37
Paper, ordinary	air dry	0.12
Pine, across grain	8	0.12-0.14
Pine, along grain	8	0.30-0.35
Plaster	6-8	0.68
Slag concrete	13	0.60
Vinyl plastic	—	0.108

Table 47

Coefficients of Pressure Change of Gases at Constant Volume

Gas	Air without CO_2	Ammonia	Carbon dioxide	Helium	Hydrogen	Nitrogen	Oxygen
Coefficient of pressure change$\times 10^3$	3.674	3.802	3.726	3.660	3.662	3.674	3.674

Table 48

Thermal Conductivities of Liquids at Various Temperatures (in kcal/m hr degree)

Substance	Temperature, °C		
	0	50	100
Acetone	0.15	0.14	0.13
Aniline	0.16	0.152	0.144
Benzene	—	0.119	0.108
Castor oil	0.158	0.152	0.147
Ethyl alcohol	0.162	0.152	—
Glycerine	—	0.243	0.248
Methyl alcohol	0.184	0.178	—
Toluene	0.122	0.111	0.102
Vaseline oil	0.108	0.105	0.102
Water	0.474	0.557	0.587

Table 49

Thermal Conductivities of Some Gases at Standard Atmospheric Pressure

Substance	Temperature, °C	Thermal conductivity, $\lambda\times 10^4$ kcal/m hr degree
Air	20	221
Argon	41	161
Carbon dioxide	20	139
Helium	43	1,340
Hydrogen	15	1,508
Methane	0	264
Nitrogen	15	216
Oxygen	20	225

Table 50

Dependence of the Lifetime of the Planetary Atmospheres on the Escape Velocity

Age of earth 3×10^9-4×10^9 years

$\frac{v \text{ escape}}{v \text{ average}}$	4	4.5	5
Lifetime (years)	50×10^3	30×10^6	25×10^9

Table 51

Standard Atmosphere

Height, m	Pressure, p/p_0	Density, ρ/ρ_0	Temperature, °C
0	1	1	15
1,000	0.887	0.907	8.5
2,000	0.784	0.822	2
3,000	0.692	0.742	−4.5
4,000	0.608	0.669	−11
5,000	0.533	0.601	−17.5
6,000	0.465	0.538	−24
7,000	0.405	0.481	−30.5
8,000	0.351	0.428	−37
9,000	0.303	0.381	−43
10,000	0.261	0.337	−50

Table 52

Diameters of Molecules

Substance	Diameter of molecules, $d\times10^8$ cm	Substance	Diameter of molecules, $d\times10^8$ cm
Argon	2.9	Krypton	3.14
Carbon dioxide	3.3	Mercury	3.0
Carbon monoxide	3.2	Nitrogen	3.2
Helium	1.9	Oxygen	2.9
Hydrogen	2.4	Xenon	4.0

Note. The diameters of the molecules have been computed from the results of measurements of the viscosity of gases.

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Table 53

Heats of Combustion of Some Fuels

The amount of heat evolved by the combustion of unit mass (or unit volume) of a fuel is called the *heat of combustion*.

Fuel	Heat of Combustion
Solid	
Anthracite (grade АП)	7,240 kcal/kg
Charcoal	7,100 "
Coal (grade Д)	4,900 "
Dynamite (75%)	1,290 "
Gunpowder	720-750 "
Peat (in lumps)	2,560 "
Shales (Esthonian)	2,300 "
Wood	2,400 "
Liquid	
Benzine	10,600 "
Black oil	9,400 "
Ethyl alcohol	6,470 "
Kerosene	10.300 "
Ligroin	10 500 "
Gas	
Carbon monoxide	3,100 kcal/m^3
Coke oven gas	3,800-4,500 "
Hydrogen	2,580 "
Illuminating gas	4,200-5,000 "
Natural gas	8,500 "

Table 54

Psychrometric Table of Relative Humidity of Air

Reading of dry bulb thermometer, °C	Difference between readings of dry and wet bulb thermometers, °C										
	0	1	2	3	4	5	6	7	8	9	10
0	100	81	63	45	28	11	—	—	—	—	—
2	100	84	68	51	35	20	—	—	—	—	—
4	100	85	70	56	42	28	14	—	—	—	—
6	100	86	73	60	47	35	23	10	—	—	—
8	100	87	75	63	51	40	28	18	7	—	—
10	100	88	76	65	54	44	34	24	14	4	—
12	100	89	78	68	57	48	38	29	20	11	—
14	100	90	79	70	60	51	42	33	25	17	9
16	100	90	81	71	62	54	45	37	30	22	15
18	100	91	82	73	64	56	48	41	34	26	20
20	100	91	83	74	66	59	51	44	37	30	24
22	100	92	83	76	68	61	54	47	40	34	28
24	100	92	84	77	69	62	56	49	43	37	31
26	100	92	85	78	71	64	58	50	45	40	34
28	100	93	85	78	72	65	59	53	48	42	37
30	100	93	86	79	73	67	61	55	50	44	39

Note. The relative humidity is determined by means of a *psychrometer* (wet and dry bulb hygrometer) which consists of two thermometers, one with a dry bulb and the other with a bulb covered by a piece of wet material. In order to determine the relative humidity from Table 54, find the intersection of the column corresponding to the measured difference between the readings of the wet and dry bulb thermometers, and the line corresponding to the reading of the dry bulb thermometer.

Table 55

Density, Pressure and Free Path of Nitrogen Molecules in the Earth's Atmosphere

Height, km	Pressure, mm Hg	Density, g/m³	Free path, cm
0	760	1,220	6.5×10^{-5}
10	210	425	1.9×10^{-5}
20	42	92	8.6×10^{-5}
30	9.5	19	4.2×10^{-4}
40	2.4	4.3	1.8×10^{-3}
50	7.5×10^{-1}	1.3	6.1×10^{-2}
80	1.0×10^{-2}	2.5×10^{-2}	3.2×10^{-1}
120	3.5×10^{-5}	5.0×10^{-5}	1.5×10^{2}
160	2×10^{-6}	1.5×10^{-6}	5×10^{3}

CHAPTER III

MECHANICAL OSCILLATIONS AND WAVE MOTION

FUNDAMENTAL CONCEPTS AND LAWS

1. Harmonic Motion

Motions (or changes of state) which to a certain extent repeat themselves at regular intervals of time are called in physics and engineering *vibrational* or *oscillatory motions* (*vibrations* or *oscillations*)

For example, in the oscillations of a small ball attached to a string the displacement of the ball to either side of the vertical position is continually repeated.

If the oscillations involve a change only of mechanical quantities (displacement, velocity, density, acceleration, etc.), then we speak of *mechanical oscillations*.

Periodic oscillations are oscillations in which each value of the variable quantity is repeated an endless number of times at regular time intervals. The smallest time interval T which elapses between two successive repetitions of some value of the variable quantity is called the *period of oscillation*.

The reciprocal of the period $\nu=\frac{1}{T}$ is called the *frequency*. The unit of frequency is the *hertz*, or cycle per second (cycle/sec). The hertz is the frequency of periodic oscillation whose period is 1 sec.

Harmonic motion is defined as periodic variation of a quantity which can be expressed as a sine or cosine function:

$$x=A\sin(\omega t+\varphi). \qquad (3,1)$$

The positive quantity A in (3,1) is called the *amplitude of harmonic motion*, $(\omega t+\varphi)$—the *phase* (or *phase angle*), φ—the *epoch angle*, ω — the *cyclic* (or *angular*) *frequency*;

$$\omega = \frac{2\pi}{T} = 2\pi\nu. \tag{3,2}$$

The phase of harmonic motion determines the value of the variable quantity at any given moment of time. The phase is expressed in units of angular measure (*radians* or *degrees*). The angular frequency is measured in radians per second (radians/sec).

An example of harmonic motion is the projection onto the x (or y) axis of the motion of a particle which is in uniform circular motion with an angular velocity ω (Fig. 19). For particles *1* and *2* the displacements of the projections are, respectively,

$$x_1 = R\sin\alpha = R\sin\omega t,$$

$$x_2 = R\sin(\alpha+\varphi) = R\sin(\omega t+\varphi).$$

Oscillations with the same frequency but different phase angles are said to be *out of phase* (or to have a *phase difference*).

The difference between the epoch angles is called the *phase difference*. The phase difference between two oscillations of the same frequency is independent of the choice of the zero of time. For example, the phase difference between the projections of particles *1* and *2* (Fig. 19) is φ for any arbitrary zero of time.

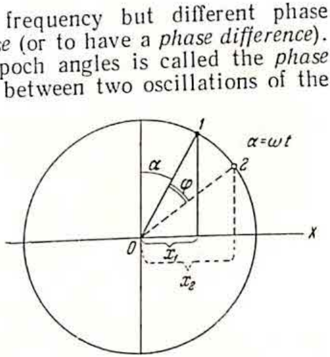


Fig. 19. Harmonic motion of projections of balls describing uniform circular motion.

Harmonic motion is produced by the action of a restoring force. A *restoring force* is a force which is proportional in magnitude to the displacement of the body from the equilibrium position and is always directed towards the equilibrium position. The mathematical expression of a restoring force is

$$F = -kx, \tag{3,3}$$

where k is a coefficient of proportionality called the *restoring force constant*, x is the displacement, and the minus sign denotes that the force is directed towards the equilibrium position.

Any kind of periodic motion can be represented to any degree of approximation by a sum of simple harmonic motions*.

2. The Pendulum

A *physical pendulum* is a rigid body which is supported at some point above its centre of gravity. A body thus supported can perform oscillations. The pendulum is called a *simple* (or *mathematical*) pendulum if the entire mass of the body can be regarded as concentrated in one point. A sufficiently close approximation of a simple pendulum is a small ball (called a pendulum bob) attached to an inextensible string, if the friction of the air and the pendulum support are negligible, and the dimensions of the ball are small compared with the length of the string. For small angular displacements the oscillations of a simple pendulum may be considered harmonic.

The period of the simple pendulum is given by the formula:

$$T = 2\pi \sqrt{\frac{l}{g}}, \qquad (3,4)$$

where l is the length of the pendulum, and g is the acceleration of gravity.

The oscillations of a bob suspended from a spring can be considered harmonic if the amplitude of oscillation lies within the limits of validity of Hooke's law (see p. 43) and frictional forces are negligible.

The period of the bob is

$$T = 2\pi \sqrt{\frac{m}{k}}, \qquad (3,5)$$

where m is the mass of the bob and k is the coefficient of elasticity of the spring, equal numerically to the force required to stretch the spring by 1 cm**.

A *torsional pendulum* is a body which performs rotary-oscillatory motion under the action of a spring (for example, the balance wheel in watches and clocks). Under certain conditions (when the amplitude of oscillation is sufficiently small and frictional forces are negligible) such motion can also be considered harmonic. The period of a torsional pendulum is given by the formula:

---

* It is shown in mathematical analysis that any periodic motion can be represented by an infinite sum of harmonic motions, called a *harmonic series*.

** Formula (3,5) applies not only to the case of a bob suspended from a spring, but also to all cases for which the relation (3,3) is valid.

$$T=2\pi\sqrt{\frac{J}{D}}, \tag{3,6}$$

where J is the moment of inertia of the body about the axis of rotation, and D is the *torsional rigidity*, equal numerically to the torque required to turn the body through unit angle.

The period of a physical pendulum is the formula:

$$T=2\pi\sqrt{\frac{J}{mga}}, \tag{3,7}$$

where J is the moment of inertia of the body about an axis passing through the point of support, a—the distance from the centre of gravity to this axis, m—the mass of the body, and g—the acceleration of gravity.

3. Free and Forced Oscillations

The oscillations which a body performs when it is in some way displaced from equilibrium and then released, are called *free* (or *natural*) oscillations.

If the free oscillations of a body are caused only by a restoring force, then they will be harmonic.

The oscillations of a body due to the simultaneous action of a restoring force and a frictional force (which is proportional to the instantaneous velocity, $F_{\text{fric}}=-rv$*, where v is the velocity) are called *damped oscillations*. The equation of damped oscillations has the form

$$x=Ae^{-\delta t}\sin(\omega t+\varphi).$$

The positive quantity A is called the *initial amplitude*, δ—the *damping constant*, $Ae^{-\delta t}$—the *instantaneous value of the amplitude*, ω—the *angular frequency*, e—the base of the natural system of logarithms;

$$\delta=\frac{r}{2m}, \tag{3,8a}$$

$$\omega=\sqrt{\frac{k}{m}-\frac{r^2}{4m^2}}, \tag{3,8b}$$

---

* The minus sign denotes that the velocity and the force are oppositely directed.

where r is the frictional force constant, m—the mass of the body, and k—the restoring force constant.

Damped oscillations are depicted graphically by the curve in Fig. 20.

The oscillations of a body under the action of periodic driving force are called *forced oscillations*.

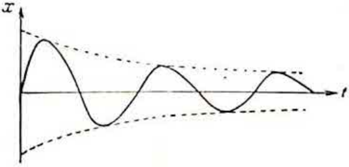


Fig. 20. Damped oscillations.

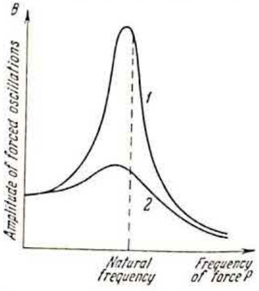


Fig. 21. Resonance curves: 1 — weak damping, 2 — strong damping.

When the period of the sinusoidal driving force approaches the period of natural oscillations of the body, the amplitude of the forced oscillations increases sharply (Fig. 21). This phenomenon is called *resonance*.

If the frictional forces are large (strong damping), then the resonance is weak (see Fig. 21).

4. Sound

Sound is produced by the mechanical vibrations of elastic media and bodies (solid, liquid and gaseous) with frequencies ranging from 17-20 to 20,000 vib/sec. Within this range of frequencies mechanical vibrations can produce the sensation of sound in the human ear. Mechanical vibrations of frequency below 17 vib/sec are called *infrasonic* (or subsonic), vibrations of frequency above 20,000 vib/sec are called *ultrasonic*.

Every musical sound is characterised by *loudness* and *pitch*. The loudness of a sound depends on the amplitude of vibration, the pitch—on the frequency.

5. Wave Motion

Wave motion is the propagation of a disturbance of some kind. For example, if we strike one end of a metal bar, a local compression arises at that end and passes along the bar with a definite velocity.

The velocity with which the disturbance advances is called the *wave velocity*. The velocity of mechanical waves depends on the properties of the medium, and in some cases on the frequency. The dependence of the wave velocity on the frequency is called *dispersion of the velocity*.

When mechanical waves are propagated in a medium the particles of the medium vibrate about equilibrium positions. The velocity of the particles of the medium is called the *velocity of vibration*.

If, when waves are propagated in a medium, the parameters characterising the medium (for example, density, particle displacement, pressure, etc.) vary at any arbitrary point in space according to a sine function, the waves are called *sine waves*.

An important characteristic of sine waves is the wavelength. The *wavelength* (λ) is defined as the distance travelled by the wave in one period:

$$\lambda = vT, \tag{3,9a}$$

$$\nu = \frac{v}{\lambda}, \tag{3,9b}$$

where v is the wave velocity, ν—the frequency, and T—the period.

The mathematical expression

$$x = A \sin \omega \left(t - \frac{r}{v}\right),$$

which describes the variation of some parameter of the medium through which sine waves are passing is called the *equation of plane harmonic waves**.

In this expression A is the *amplitude of the wave*, ω—the cyclic frequency, r—the distance from the source initiating the wave to the point of interest in the medium, v—the velocity of the wave; the expression $\omega\left(t - \frac{r}{v}\right)$ is called the *phase of the wave*.

The surface, obtained by connecting all points which have a common phase, is called a *wave front*.

According to the shape of the wave front we distinguish between *plane*, *cylindrical* and *spherical* waves.

---

* Here x denotes any parameter characterising the state of the medium (for example, pressure, temperature, etc.).

We distinguish between longitudinal and transverse waves, depending on how the particles of the medium are displaced with respect to the direction of propagation of the wave.

In a *longitudinal* wave the particles of the medium oscillate in the direction of propagation; in a *transverse* wave they oscillate perpendicular to the direction of propagation of the wave. Mechanical waves in liquids and gases are longitudinal.

The velocity of longitudinal waves in a rod is given by the formula:

$$v_l = \sqrt{\frac{E}{\rho}}, \tag{3,10a}$$

where E is Young's modulus and ρ is the density.

The velocity of longitudinal waves in a solid, the transverse dimensions of which are much greater than the wavelength, is

$$v_l = \sqrt{\frac{E}{\rho} \times \frac{1-\mu}{(1+\mu)(1-2\mu)}}, \tag{3,10b}$$

where ρ is the density of the medium, E—Young's modulus, and μ—Poisson's ratio (see Table 17).

The velocity of longitudinal waves in fluids is given by the formula:

$$v_l = \sqrt{\frac{\gamma}{\rho \beta_t}}, \tag{3,11}$$

where β_t is the *isothermal compressibility* *, $\gamma = \frac{c_p}{c_v}$.

The velocity of transverse waves is given by

$$v_t = \sqrt{\frac{G}{\rho}}, \tag{3,12}$$

where G is the modulus of shear.

The velocity of sound waves in gases is expressed by the formula:

$$v_{\text{sound}} = \sqrt{\gamma \frac{p}{\rho}}, \tag{3,13a}$$

where $\gamma = \frac{c_p}{c_v}$, and p is the pressure.

---

* For compressibility see p. 43. Isothermal compressibility — compression takes place at constant temperature.

Formula (3,13) applies to ideal gases, in which case it can be written in the form:

$$v_{\text{sound}} = \sqrt{\gamma \frac{RT}{\mu}} \tag{3,13b}$$

Waves on the surface of a liquid are neither transverse, nor longitudinal. The particles of a liquid describe more complex motions in surface waves (Fig. 22).

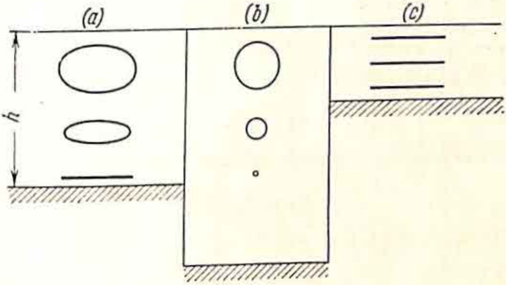


Fig. 22. Trajectories of particles of water in surface waves: *a*) shallow water, *b*) very deep water (very large ratio $\frac{2\pi h}{\lambda}$), *c*) very shallow water (very small ratio $\frac{2\pi h}{\lambda}$).

The velocity of surface waves * is given by

$$v_{\text{sur}} = \sqrt{\frac{g\lambda}{2\pi} + \frac{2\pi\alpha}{\lambda\rho}}, \tag{3,14}$$

where g is the acceleration of gravity, λ—the wavelength, α—the surface tension, and ρ—the density.

Formula (3,14) applies when the depth of the liquid is not less than 0.5λ.

When the depth of the liquid h is less than 0.5λ, the velocity is expressed by the formula:

$$v_{\text{sur}} = \sqrt{gh}. \tag{3,15}$$

Wave motion is accompanied by the transfer of energy; the particles of the medium, however, are not carried along with the wave but only oscillate about their equilibrium positions (if the waves are of small amplitude and the medium is non-viscous).

---

* Formula (3,14) applies to waves on a liquid-gas interface, when the density of the liquid is much greater than that of the gas.

The mean quantity of energy transmitted per second across 1 square centimeter perpendicular to the direction of propagation of the wave is called the *intensity of the wave.*

Intensity is expressed in watts/cm^2 or ergs/cm^2 sec.

When mechanical waves travel through a medium the velocity and acceleration of the particles of the medium vary according to the same sine law as does the displacement.

If the amplitude of displacement of the particles is x_0 when a sine wave of cyclic frequency ω passes through the medium, then the amplitude of vibration of the particles will be

$$u_0 = \omega x_0, \tag{3,16}$$

the amplitude of acceleration of the particles

$$a_0 = \omega^2 x_0, \tag{3,17}$$

and the intensity of the wave

$$I = \frac{1}{2}\rho v u_0^2, \tag{3,18}$$

where ρ is the density of the medium, v—the wave velocity, and u_0—the maximum velocity of vibration of the particles.

The maximum increase in pressure in the medium (Δp_0) due to the propagation of sound waves is called the *sound pressure.* The following relation exists between the sound pressure and the maximum velocity of vibration of the particles:

$$\Delta p_0 = \rho v u_0. \tag{3,19}$$

The intensity of sound corresponds to the subjective sensation of loudness. Below a certain minimum intensity, called the *threshold of audibility*, sound is no longer audible to the human ear. The threshold of audibility is different for sounds of different frequencies. Sound of great intensity produces a painful sensation in the ear. The smallest intensity of sound causing such a sensation is called the *threshold of feeling.*

A change in intensity (intensity level) is expressed in *decibels* (db).

The intensity level B of a sound is defined as

$$B = 10 \log \frac{I}{I_0}.$$

As a rule, in acoustics I_0 is taken equal to 10^{-9} erg/cm²sec, which is approximately equal to the threshold of audibility at 1,000 c/sec.

Mechanical waves, like electromagnetic waves (see Chapter V: Optics) undergo reflection, refraction, diffraction and interference.

TABLES AND GRAPHS

Table 56

Velocity of Sound in Pure Liquids and Oils

Liquid	Temperature, °C	Velocity, m/sec	Temperature coefficient, m/sec degree
Pure liquids			
Acetone	20	1,192	−5.5
Aniline	20	1,656	−4.6
Benzene	20	1,326	−5.2
Ethyl alcohol	20	1,180	−3.6
Glycerine	20	1,923	−1.8
Heavy water	25	1,399	2.8
Mercury	20	1,451	−0.46
Methyl alcohol	20	1,123	−3.3
Ordinary water	25	1,497	2.5
Sea water	17	1.510-1.550	—
Oils			
Cedar nut	29	1,406	—
Eucalyptus	29.5	1,276	—
Gasoline	34	1,250	—
Hemp seed	31.5	1,772	—
Kerosene	34	1,295	—
Olive	32.5	1,381	—
Peanut	31.5	1,562	—
Rapeseed	30.8	1,450	—
Spindle	32	1,342	—
Transformer	32.5	1,425	—

Note. The velocity of sound in liquids decreases with a rise in temperature (with the exception of water). The velocity at temperatures other than those given in the table can be computed from the formula: $v_t=v_0\ [1+\alpha\ (t-t_0)]$, where v_0 is the velocity given in the table, α—the temperature coefficient given in the last column of the table for pure liquids, t—the temperature for which the velocity is sought, and t_0—the temperature indicated in the table.

Table 57

Velocity of Sound in Solids at 20° C

Material	Velocity of longitudinal waves in rods, m/sec	Velocity of longitudinal waves in infinite medium, m/sec	Velocity of transverse waves in infinite medium, m/sec
Aluminium	5,080	6,260	3,080
Brass	3,490	4,430	2,123
Caoutchouc	—	1,479	—
Coal (briquettes)	—	3,700	2,000
Copper	3,710	4,700	2,260
Cork	500	—	—
Ebonite	1,570	2,405	—
Glass, crown	5,300	5,660	3,420
" heavy crown	4,710	5,260	2,960
" heavy flint	3,490	3,760	2,220
" light flint	4,550	4,800	2,950
" silica	5,370	5,570	3,515
Hematite, brown	—	1,830	—
Ice	3,280	3,980	1,990
Iron	5,170	5,850	3,230
Lead	2,640	3,600	1,590
Limestone	—	6,130	3,200
Marble	—	6,150	3,260
Mica	—	7,760	2,160
Nickel	4,785	5,630	2,960
Plaster of Paris	—	4,970	2,370
Plexiglas	—	2,670	1,121
Polystyrene	—	2,350	1,120
Porcelain	4,884	5,340	3,120
Rubber	46	1,040	27
Sandstone	—	3,700-4,900	—
Slate	—	5,870	2,800
Steel, carbon	5,050	6,100	3,300
Tin	2,730	3,320	1,670
Tungsten	4,310	5,460	2,620
Zinc	3,810	4,170	2,410

Table 58

Velocity of Seismic Waves

Mechanical waves travelling in the earth's crust are called *seismic waves*.

Seismic waves can be longitudinal (compressional waves) or transverse (shear waves).

Depth, km	Velocity of longitudinal waves, km/sec	Velocity of transverse waves, km/sec
0-20	5.4-5.6	3.2
20-45	6.25-6.75	3.5
1,300	12.5	6.9
2,400	13.5	7.5

Table 59

Velocity of Sound in Gases at 1 atm

Gas	Temperature, °C	Velocity, m/sec	Temperature coefficient, m/sec degree
Air	0	331	0.59
Ammonia	0	415	—
Benzene (vapour)	97	202	0.3
Carbon dioxide	0	259	0.4
Deuterium	0	890	1.6
Ethyl alcohol	97	269	0.4
Helium	0	965	0.8
Hydrogen	0	1,284	2.2
Methyl alcohol	97	335	0.46
Neon	0	435	0.8
Nitrogen	0	334	0.6
Oxygen	0	316	0.56
Water vapour	134	494	—

Notes. 1. The velocity of sound in gases at constant pressure increases with increase in the temperature. The temperature coefficient of the velocity is therefore given in the table, so that the velocity can be computed for other temperatures.

2. At high frequencies (or low pressures) the velocity of sound depends on the frequency. The values given in the table are for frequencies and pressures at which the velocity is practically independent of the frequency

Sound Velocity Versus Pressure in Air and Nitrogen

The curves of Fig. 23 refer to 25°C and the frequency range from 200 Kc/sec to 500 Kc/sec.

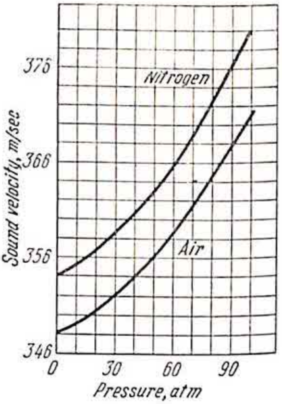


Fig. 23.

Sound Frequency Spectrum

Fig. 24 gives the spectrum of sound frequencies divided into octaves as is customary in music. The piano keyboard is depicted alongside the spectrum; it covers practically all the frequencies used in music. The ratio of the frequencies of two musical tones is called an *interval*. An *octave* is an interval with a frequency ratio $\frac{\nu_2}{\nu_1} = 2$.

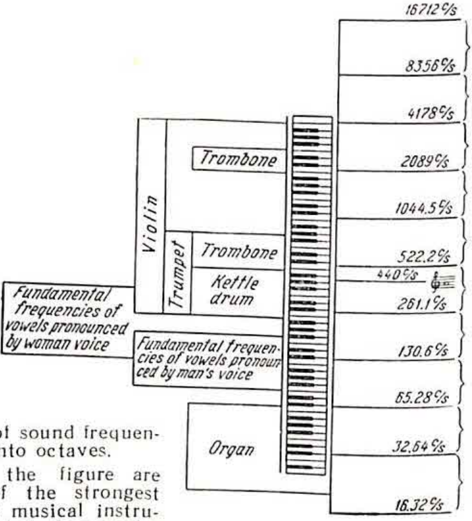


Fig. 24. Spectrum of sound frequencies, divided into octaves.

On the left of the figure are shown the range of the strongest frequencies of some musical instruments and the loudest frequencies of men's and women's voices in pronouncing vowels. The frequencies are plotted logarithmically.

Velocity of Water Surface Waves

At small wavelengths (less than 2 cm) the decisive factor is the surface tension: such waves are called *capillary waves*.

At greater wavelengths the decisive factor is gravity, and the waves are called *gravity waves*. The velocity of surface waves depends on the wavelength (see (3.14)), if the depth of the liquid is sufficiently great ($h > 0.5\lambda$).

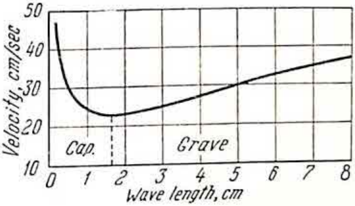


Fig. 25. Dispersion of surface waves ($h > 0.5\lambda$).

Loudness of Audibly Perceived Sounds

Fig. 26 gives the curves of intensity of sounds of equal loudness. The upper curve corresponds to the threshold of feeling, the lower – to the threshold of audibility. The frequencies are plotted on a logarithmic scale.

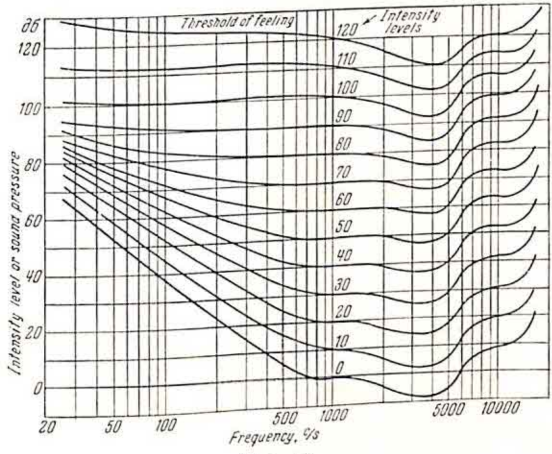


Fig. 26.

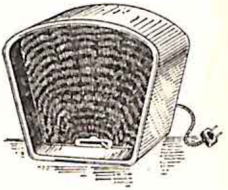
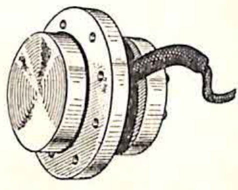
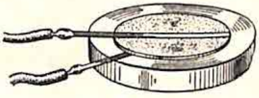
Frequency		Emitter	
0.5 cycle/sec— 1 cycle/sec— 20 cycles/sec—	Infrasonic	Low-frequency vibrations of bodies	
100 cycles/sec— 1 Kc/sec— 10 Kc/sec—	Audible	Voices of human beings, animals, etc. Musical instruments, whistles, sirens, loudspeakers, etc.	
20 Kc/sec— 1 Mc/sec— 10 Mc/sec—	Ultrasonic	Ultrasonic sirens and whistles, magnetostrictive and piezoelectric oscillators, etc.	
10^2 Mc/sec— 10^3 Mc/sec—		Piezoelectric oscillators (quartz, barium titanate, tourmaline, etc.)	
10^4 Mc/sec— 10^5 Mc/sec— 10^6 Mc/sec—		Thermal vibrations of molecules	

Fig 27. Spectrum of mechanical

Field of application		Natural occurrence
		Vibrations of water in natural reservoirs and vibrations of bodies (frequencies below 16 cycles/sec) Sound of heartbeats
Communication and signalisation; measurement of distance by means of sound		Voices of human beings, animals, birds, insects. Sounds of various natural phenomena (wind, thunder, flowing water, etc.)
Sonar	Ultrasonic cleaning of parts; application in medicine and biology	Emitted by bats, crickets, locusts
Ultrasonic fault detection in metals, concrete, etc. Ultrasonic microscope		
Scientific research		
Scientific research		

vibrations (logarithmic scale).

Displacement, Velocity and Acceleration of Water Particles due to Passage of Sound Waves of Various Intensities

Figs. 28, 29, 30 give the amplitudes of the displacement, velocity and acceleration, computed from formulas (3,16), (3,17) and (3,18). The computations have been carried out for $\varrho v = 1.5 \times 10^5$ g/cm² sec. The scales on both axes are logarithmic.

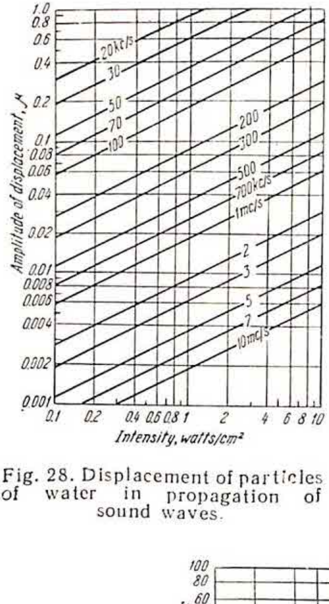


Fig. 28. Displacement of particles of water in propagation of sound waves.

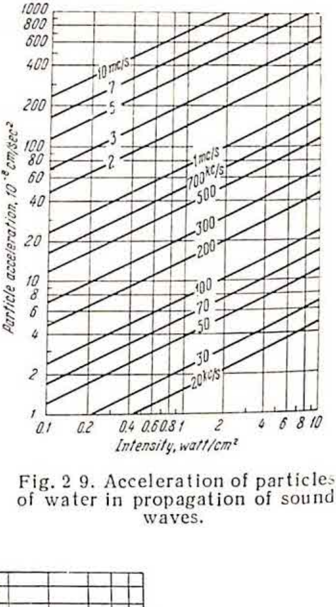


Fig. 29. Acceleration of particles of water in propagation of sound waves.

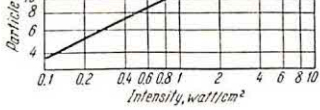


Fig. 30. Velocity of particles of water in propagation of sound waves.

Table 60

Sound Intensity and Sound Pressure Corresponding to the Main Frequencies of the Decibel Scale

Decibel scale	Sound intensity, watt/cm²	Sound pressure, dynes/cm²	Sounds of the given intensity
0	10^{-16}	0.0002	Threshold of audibility of the human ear
10	10^{-15}	0.00065	Rustle of leaves. Low whisper at a distance of 1 m.
20	10^{-14}	0.002	Quiet garden.
30	10^{-13}	0.0065	Quiet room. Average sound level in an auditorium. Violin playing pianissimo
40	10^{-12}	0.02	Low music. Noise in a living room.
50	10^{-11}	0.065	Loudspeaker at low volume. Noise in a restaurant or office with open windows
60	10^{-10}	0.2	Radio turned on loud. Noise in a store. Average level of speech at a distance of 1 m.
70	10^{-9}	0.645	Noise of a truck motor. Noise inside a tramcar.
80	10^{-8}	2.04	Noisy street. Typists' room.
90	10^{-7}	6.45	Automobile horn. Large symphony orchestra playing fortissimo.
100	10^{-6}	20.4	Riveting machine. Automobile siren.
110	10^{-5}	64.5	Pneumatic hammer.
120	10^{-4}	200	Jet engine at a distance of 5 m. Loud thunderclaps.
130	10^{-3}	645	Threshold of feeling, sound is no longer audible

Table 61

Reflection Coefficient of Sound Waves for Various Interfaces (at normal incidence), %

The *reflection coefficient* is defined as the ratio of the intensities of the reflected and incident sound waves.

Material	Aluminium	Copper	Glass	Mercury	Nickel	Steel	Transformer oil	Water
Aluminium	0	18	2	1	24	21	74	72
Copper		0	19	13	0.8	0.3	88	87
Glass			0	4	34	31	67	65
Mercury				0	19	16	76	75
Nickel					0	0.2	90	89
Steel						0	89	88
Transformer oil							0	0.6
Water								0

Notes. 1. The reflection coefficient is the same for sound passing from mercury into steel and vice versa.

2. Upon reflection from a plate the reflection coefficient depends on the ratio of the thickness of the plate to the wavelength.

Table 62

Absorption Coefficient of Sound in Different Materials

The *absorption coefficient* of sound (upon reflection) is defined as the ratio of the energy absorbed to the energy incident on the reflecting surface.

Material \ Frequency, c/sec	125	250	500	1,000	2,000	4,000
Brick wall (unplastered)	0.024	0.025	0.032	0.041	0.049	0.07
Cotton material	0.03	0.04	0.11	0.17	0.24	0.35
Glass, sheet	0.03	—	0.027	—	0.02	—
Glass wool (9 cm thick)	0.32	0.40	0.51	0.60	0.65	0.60
Hair felt (25 mm thick)	0.18	0.36	0.71	0.79	0.82	0.85
Marble	0.01	—	0.01	—	0.015	—
Plaster, gypsum	0.013	0.015	0.020	0.028	0.04	0.05
Plaster, lime	0.025	0.045	0.06	0.085	0.043	0.058
Rug with nap	0.09	0.08	0.21	0.27	0.27	0.37
Wooden planking	0.10	0.11	0.11	0.08	0.082	0.11

CHAPTER IV

ELECTRICITY

A. THE ELECTROSTATIC FIELD

FUNDAMENTAL CONCEPTS AND LAWS

There are *two kinds* of electric charges—positive and negative. *Positive* charges are the kind which are generated on a glass rod which has been rubbed with silk, and also charges which are repelled by them. *Negative* charges are the kind which are generated on an ebonite rod when rubbed with fur, and also the charges which are repelled by them.

Like charges repel each other, unlike charges attract each other.

Interaction of charges. Electric field. The law of interaction of point charges was established experimentally by Coulomb: in the CGSE system

$$F=\frac{q_1q_2}{\varepsilon r^2}, \tag{4,1}$$

and in the SI system

$$F=\frac{q_1q_2}{4\pi\varepsilon_0\varepsilon r^2}$$

where F is the force of interaction, q_1 and q_2—the magnitudes of the charges, r—the distance between them, and ε—a quantity called the *relative dielectric constant of the medium.* In the case of vacuum the dielectric constant is denoted by ε_0,

$$F=\frac{q_1q_2}{\varepsilon_0 r^2}. \tag{4,2}$$

In the CGSE system of units $\varepsilon_0=1$; in the SI system

$$\varepsilon_0=1/36\pi\times10^9 \text{ farad/m}$$

The CGSE unit of charge is defined as that charge which when placed 1 cm from an equal charge in vacuum exerts upon it a force of 1 dyne. The practical unit of charge (SI system) is the *coulomb*:

1 coulomb$=2.99793\times10^9$ CGSE units $\cong3\times10^9$ CGSE units.

The magnitude of any electric charge is always a multiple of a certain minimum charge, called the *elementary charge* (e); $e = 4.8 \times 10^{-10}$ CGSE units.

A region in which electric forces act is called an *electric field*. Electrically charged bodies are always surrounded by an electric field. The field due to fixed charges is called an *electrostatic field*. The force acting on unit positive charge placed at a given point is called the *intensity* of the electric field at that point:

$$E = \frac{F}{q}. \tag{4,3}$$

The intensity is a vector quantity. The direction of the intensity coincides with that of the force acting on a positive charge. The field intensities due to two separate electric charges are added according to the parallelogram law, i. e., by vector methods.

The electrostatic field intensity of a point charge* is

$$E = \frac{q}{\varepsilon r^2}, \tag{4,4}$$

where r is the distance from the point for which the intensity is sought to the charge.

The electric field intensity of a uniformly charged surface is

$$E = \frac{2\pi\sigma}{\varepsilon}, \tag{4,5}$$

where σ is the charge per unit surface.

The electric field intensity of a uniformly charged sphere is

$$E = \frac{q}{\varepsilon r^2}, \tag{4,6}$$

where r is the distance from the point for which the intensity is sought to the center of the sphere.

The electric field intensity of a charged cylinder is

$$E = \frac{2q'}{\varepsilon r}, \tag{4,7}$$

where q' is the charge per unit length along the axis of the cylinder, and r is the distance from the point of interest to the axis of the cylinder.

---

* All the following formulas are given in the CGSE system, unless otherwise specified.

The *lines of force* of an electric field are defined as curves, the tangents to which at each point coincide in direction with the intensity vector. The lines of force of various electric fields are illustrated in Figs. 31, 32 and 33.

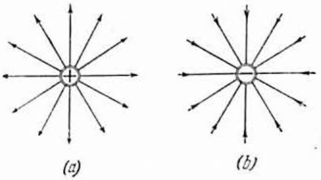


Fig. 31. Lines of force of point charges: *a*) positive, *b*) negative.

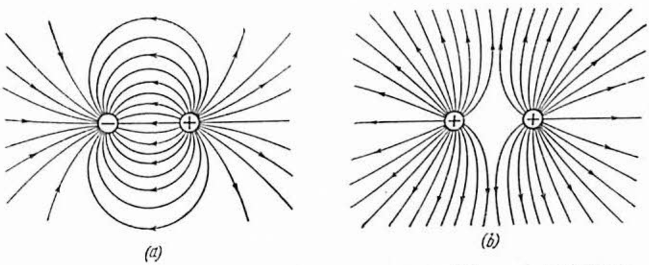


Fig. 32. Lines of force: *a*) field of two unlike point charges, *b*) field of two like point charges.

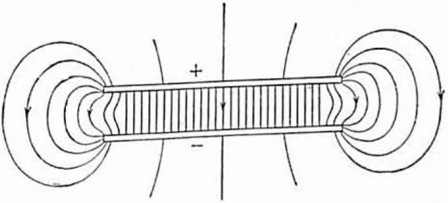


Fig. 33. Electric field of parallel plate condenser.

Work and potential. When a charge is displaced under the influence of an electric field work is performed. In an electrostatic field the magnitude of the work performed is independent of the path of the charge. The work performed by the electric forces in moving unit positive charge from one point to another is defined as the *potential difference* between the two points (U). The potential at a point is defined as the potential difference between that point and an arbitrarily chosen point of zero potential. The point of zero potential is frequently taken at infinity. The work of displacement of a charge q in an electrostatic field is

$$A = qU. \tag{4,8}$$

The unit of potential in the SI system is the *volt* (v), defined as the potential difference between two points when work equal to 1 joule must be performed to bring 1 coulomb of positive charge from one point to the other. A surface, all points of which are at the same potential, is called an *equipotential surface*.

The lines of force of the field are perpendicular to the equipotential surfaces. No work is done by the electric forces in moving a charge from one point to another on an equipotential surface. Let A and B be two points of the field; then the following approximate relation exists between the intensity of the field at the point A and the potential difference between these points:

$$E_A = -\frac{\Delta U}{\Delta l}, \tag{4,9}$$

where ΔU is the potential difference between the close-lying points A and B, and Δl is the distance along the line of force between the equipotential surfaces passing through these points.

If the electric field is homogeneous, i. e., if the intensity is constant in magnitude and direction at all points of the field (for example, in a parallel plate capacitor), then

$$E = -\frac{U}{l},$$

where l is the length of the line of force. In the SI system the intensity is expressed in volts/meter (v/m). 1 v/m is equal to the intensity of a homogeneous field in which the potential difference between the ends of a line of force 1 m long is equal to 1 v. The potential difference per unit length of a line of force in a homogeneous field is called the *potential gradient*.

Capacitance. Two conductors with an electric field between them whose lines of force emanate from one conductor and terminate on the other form a *capacitor*; the conductors themselves are called the *capacitor plates*.

In a simple capacitor the two plates carry opposite charges of equal magnitude.

The *capacitance* of a capacitor is defined as the ratio of the charge on one of the plates to the potential difference between the plates, i. e.,

$$C=\frac{q}{U}. \qquad (4,10)$$

The SI unit of capacitance is the *farad*. 1 farad is equal to the capacitance of a capacitor, the potential difference between whose plates is equal to 1 v when the charge (on one of the plates) is 1 coulomb. The CGSE unit of capacitance is the *centimeter* (cm).

According to the shape of the conducting surfaces capacitors are called *parallel plate*, *cylindrical* and *spherical*.

The capacitance of a parallel plate capacitor (in the CGSE system) is

$$C=\frac{\varepsilon S}{4\pi d}, \qquad (4,11)$$

where S is the surface area of one plate (the smaller one in case they are unequal), d—the distance between the plates, ε—the dielectric constant.

The capacitance of a cylindrical capacitor and of a coaxial cable is

$$C=\frac{\varepsilon l}{2\ln\frac{b}{a}}, \qquad (4,12)$$

where b is the radius of the outer cylinder, a—the radius of the inner cylinder, and l—the length of the capacitor.

The capacitance of a spherical capacitor is

$$C=\frac{\varepsilon}{\frac{1}{a}-\frac{1}{b}}, \qquad (4,13)$$

where a and b are the radii of the inner and outer spheres.

The capacitance of a two-wire line is

$$C=\frac{\varepsilon l}{4\ln\frac{d}{a}}, \qquad (4,14)$$

where d is the distance between the axes of the wires, a—their radius, and l—the length.

The capacitance of a multiple capacitor is

$$C=\frac{0.088\varepsilon S(n-1)}{d}, \tag{4,15}$$

where S is the area of one plate, n—the number of plates, d—the distance between two adjacent plates.

If capacitors of separate capacitances $C_1, C_2, C_3, \ldots, C_n$ are connected in parallel the capacitance of the whole system is

$$C_{\text{par}}=C_1+C_2+C_3+\ldots+C_n, \tag{4,16}$$

for a system of capacitors connected in series the capacitance is

$$\frac{1}{C_{\text{ser}}}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\ldots+\frac{1}{C_n}. \tag{4,17}$$

The energy stored in a charged capacitor is given by the formula

$$W=\frac{1}{2}CU^2. \tag{4,18}$$

The space in which an electric field exists contains stored energy. The energy in unit volume of a homogeneous field (*energy density*) can be computed by the formula (in the CGSE system)

$$w=\frac{\varepsilon E^2}{8\pi}, \tag{4,19}$$

where E is the field intensity*.

Conductors and insulators in an electric field. When a conductor is placed in an electric field charges of unlike sign are induced on it (charging by *induction*). These charges are distributed over the surface of the conductor in such manner that the intensity of the electrostatic field inside the conductor is zero, and the surface of the conductor is an equipotential surface.

---

* In the case of an *inhomogeneous* field one defines the "energy density at a point":

$$w=\lim_{\Delta V\to 0}\frac{\Delta W}{\Delta V}$$

Here ΔW is the energy concentrated in the volume ΔV when the latter "contracts" to a point. If we define E as the intensity at this point, then formula (4,19) is valid for an arbitrary field.

Insulators (dielectrics), when placed in an electric field, become *polarised*, i.e., the charges of the molecules are displaced in such manner that their external electric field resembles the field of two unlike point charges of equal magnitude (see Fig. 32, *a*).

In general, a system of charges whose external field resembles the field of two unlike point charges of equal magnitude is called an *electric dipole* (Fig. 34).

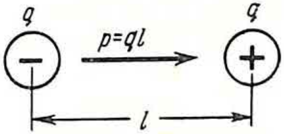


Fig. 34. Electric dipole.

The dipole is characterised by a vector quantity called the *electric dipole moment* (p_i):

$$p_i = ql, \qquad (4{,}20)$$

where l is the distance between the charges.

The direction of the vector p_i is taken from $-q$ to $+q$.

The vector sum of all the moments of the elementary dipoles in a unit volume is called the *polarisation* of the dielectric:

$$p = \sum p_i \qquad (4{,}21)$$

The molecules of some dielectrics are dipoles even in the absence of an electric field. In the case of such substances polarisation consists in an alignment of the elementary dipoles in the direction of the field.

Ferroelectrics (seignette-electrics). Some dielectrics even in the absence of an electric field contain small (microscopic) regions which are polarised in different directions. Such dielectrics are called *ferroelectrics*. The magnitude of their polarisation is characterised by the vector of intrinsic (*spontaneous*) polarisation $\boldsymbol{p_s}$. The properties of a ferroelectric (e. g., its dielectric constant, etc.) depend on the magnitude of the vector $\boldsymbol{p_s}$. The dielectric constants of ferroelectrics are usually large and depend to a considerable degree on the intensity of the electric field. A substance exhibits ferroelectric properties at temperatures which do not exceed a certain temperature called the *Curie point* (T_C).

The piezoelectric effect. Upon the mechanical deformation of some crystals along given directions electric charges of opposite sign appear on different faces of the crystal, while inside the crystal an electric field arises. A change in the direction of the deformation causes a change in the sign of the charges. This phenomenon is called the *piezoelectric effect*. The piezoelectric effect is reversible, i.e., when a crystal is placed in an electric field its linear dimensions change. The inverse piezoelectric effect is utilised to generate ultrasonic frequencies. The magnitude of the charge which arises in the piezoelectric effect is given by the relation

$$q = d_{11}F_x,$$

where F_x is the force causing deformation, and d_{11} is a constant for the given crystal called the *piezoelectric constant*.

TABLES AND GRAPHS

Table 63

Electric Field in the Earth's Atmosphere

Altitude, km	0	0.5	1.5	3	6	12
Intensity, v/m . . .	130	50	30	20	10	2.5

Notes. 1. The charge of a thundercloud is equal to 10-20 coulombs (in some cases it may be as much as 300 coulombs).

2. The mean surface density of charge of the earth is 3.45×10^{-4} CGSE units/cm^2. The total charge of the earth is 0.57×10^{6} coulombs

Table 64

Insulating Materials

Material	Dielectric constant, (CGSE units)	Dielectric strength, kv/mm	Density, g/cm³	Resistivity, ohm cm
Asbestos	—	2	2.3-2.6	2×10^5
Bakelite	4-4.6	10-40	1.2	—
Beeswax	2.8-2.9	20-35	0.96	2×10^{10}-2×10^{15}
Birch, dry	3-4	40-60	0.7	—
Bitumen	2.6-3.3	6-15	1.2	—
Carbolite (P)	—	10-14.5	1.2-1.3	—
Celluloid	3-4	30	—	2×10^{10}
Ebonite (RP)	4-4.5	25	1.3	1×10^{18}
Eskapon (P)	2.7-3	36	—	—
Fibre board, dry	2.5-8	2-6	1.1-1.94	5×10^9
Fluoplastic-3	2.5-2.7	—	2.14	1.2×10^{18}
Getinax (laminated insulation) (P)	5-6.5	10-30	1.3	—
Glass	4-10	20-30	2.2-4.0	10^{11}-10^{14}
Gutta percha	4	15	0.95	2×10^9
Marble	8-10	6-10	2.7	1×10^{10}
Mica, muscovite	4.5-8	50-200	2.8-3.2	—
Mica, phlogopite	4-5.5	60-125	2.5-2.7	10^{13}-10^{17}
Paraffin	2.2-2.3	20-30	0.4-0.9	3×10^{18}
Plexiglass	3.0-3.6	18.5	1.2	—
Polystyrene	2.2-2.8	25-50	1.05-1.65	5×10^{15}-5×10^{17}
Polyvinyl chloride resin	3.1-3.5	50	1.38	—
Porcelain, electrical	6.5	20	2.4	3×10^{14}
Pressboard	3-4	9-12	0.9-1.1	1×10^9
Radioporcelain (C)	6.0	15-20	2.5-2.6	—
Rosin	3.5	—	1.1	5×10^{16}
Rubber, soft	2.6-3	15-25	1.7-2.0	4×10^{13}
Shellac	3.5	50	1.02	1×10^{16}
Silk, natural	4-5	—	—	—
Slate	6-7	5-14	2.6-2.9	10^8
Textolite	7	2-8	1.3-1.4	—
Ticond (C)	25-80	15-20	3.8-3.9	—
Ultraporcelain (C)	6.3-7.5	15-30	2.6-2.9	3×10^{14}
Vinyl plastic (P)	4.1	15	—	—

Notes. 1. The dielectric strength characterises the maximum potential difference which can be applied to a dielectric without destroying its insulating properties.

2. The letters in the parentheses denote: (P) — plastic, (C) — ceramic, (RP) — rubber plastic.

3. The values of the dielectric constant are given for temperatures 18 to 20°C. The dielectric constants of solids vary but slightly with the temperature, with the exception of ferroelectrics (see Figs. 35, 36).

4. For resistivity refer to p. 111.

Table 65

Dielectric Constants of Some Pure Liquids (CGSE System of Units)

Substance	Temperature						
	0°C	10°C	20°C	25°C	30°C	40°C	50°C
Acetone	23.3	22.5	21.4	20.9	20.5	19.5	18.7
Benzene	—	2.30	2.29	2.27	2.26	2.25	2.22
Carbon tetrachloride	—	—	2.24	2.23	—	2.20	2.18
Ethyl alcohol	27.88	26.41	25.00	24.25	23.52	22.16	20.87
Ethyl ether	4.80	4.58	4.38	4.27	4.15	—	—
Glycerine	—	—	56.2	—	—	—	—
Kerosene	—	—	2.0	—	—	—	—
Water	87.83	83.86	80.08	78.25	76.47	73.02	69.73

Note. Small quantities of impurities have a negligible effect on the value of the dielectric constant.

Table 66

Dielectric Constants of Gases at 18°C and Normal Pressure

Substance	ε	Substance	ε
Air	1.00059	Nitrogen	1.00061
Carbon dioxide	1.00097	Oxygen	1.00055
Helium	1.00007	Water vapour	1.0078
Hydrogen	1.00026		

Note. The dielectric constants of gases decrease with an increase in the temperature, and increase with an increase in the pressure.

Table 67

Some Properties of Ferroelectric Crystals

Crystal	Curie point, °K	Vector of spontaneous polarisation, (CGSE units)	Dielectric constant
$NaK(C_4H_4O_6)\cdot 4H_2O$ (Rochelle salt)	297 (upper) 255 (lower)	800	200
$NaK(C_4H_2D_2O_6)\cdot 4D_2O$	308 (upper) 249 (lower)	—	—
$LiNH_4\ (C_4H_4O_6)\cdot H_2O$	106	630	—
KH_2PO_4 (potassium dihydrophosphate)	123	16,000	45
RbH_2PO_4	147		
KH_2AsO_4	96.5		
$NH_4H_2PO_4$ (ammonium dihydrophosphate)	—	—	58
$BaTiO_3$ (barium titanate)	391	48,000	1,000-1,700
$KNbO_3$	708	—	—
$NaNbO_3$	913	—	—
$LiTiO_3$	—	70,000	—

Notes. 1. Ferroelectrics are divided into three groups according to their chemical formulas.

2. Some ferroelectrics exhibit their specific properties within a given range of temperatures. For these the table indicates the upper and lower Curie points.

3. The values of the dielectric constants are given for weak fields.

4. The symbol D denotes heavy hydrogen (deuterium).

Dependence of Dielectric Constant of Ferroelectrics on the Temperature and Field Intensity

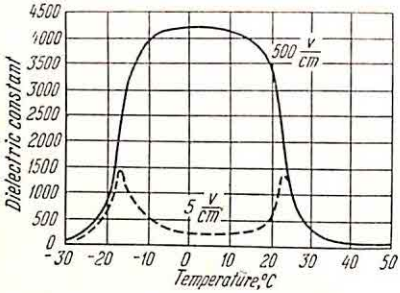


Fig. 35. Temperature dependence of dielectric constant of Rochelle salt. The two curves correspond to two different values of the field intensity.

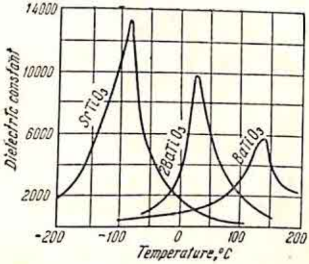


Fig. 36. Temperature dependence of dielectric constant of ferroelectrics of the barium titanate group.

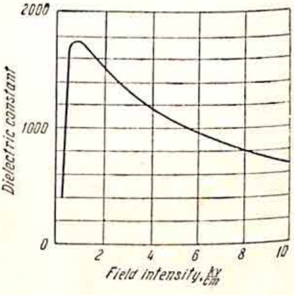


Fig. 37. Dependence of dielectric constant of a ferroelectric ceramic on the field intensity.

Table 68

Piezoelectric Constants of Some Crystals

Crystal	Piezoelectric constant, CGSE units ($d_{11}\times10^8$)
Ammonium phosphate (АДР)	148
Polarised barium titanate ceramic	750
Potassium phosphate (КДР)	70
Quartz	6.9
Rochelle salt	7,000
Tourmaline	5.78
Zinc blende	9.8

Notes. 1. Some crystals have different constants for different directions of deformation; in such cases the greatest values are given.

2. In order to convert the value of the constant from CGSE to SI units multiply the figure given in the table by 3×10^4. The constant will then be expressed in coulombs/newton.

B. THE ELECTRIC CURRENT. DIRECT-CURRENT CIRCUITS

FUNDAMENTAL CONCEPTS AND LAWS

1. Electric Current in Metals

The orderly motion of charge carriers constitutes an *electric current*. In metals the charge carriers are electrons—negatively charged particles whose charge is equal to the elementary charge. The direction of the current is arbitrarily defined as the direction opposite to that in which the negative charges move.

If a charge Δq passes through a cross-section of a conductor in a time from t_0 to $t_0+\Delta t$ then the *current* at the instant t_0 (or the *instantaneous current*) is defined as the limit

$$i_{t0}=\lim_{\Delta t\to 0}\frac{\Delta q}{\Delta t}. \qquad (4,22)$$

In a *steady current* equal charges pass through a cross-section of the conductor in equal time intervals. The unit of current in the SI system is the *ampere*, defined as a rate of flow of one coulomb per second.

The *current density* (j) is defined as the current passing through a unit cross-sectional area of the conductor. The practical unit of current density is the ampere/cm^2, i. e., a current of one ampere through an area of 1 cm^2 perpendicular to the direction of flow.

The current density is

$$j = nev, \tag{4,23}$$

where n is the number of charge carriers in unit volume, e—the charge of a carrier, and v—the mean velocity of the carriers.

If there are charges of different sign and magnitude present, the total current density will be equal to the sum of the densities due to the different kinds of charges

$$j = \sum nev. \tag{4,24}$$

The following relation also holds

$$j = \sigma E, \tag{4,25}$$

where E is the electric field intensity inside the conductor, and σ is the conductivity of the conductor (see below).

The current is a scalar quantity, the current density—a vector quantity.

For an electric current to flow in a closed circuit there must be forces other than electrostatic forces acting on the charge carriers. Any device which gives rise to such forces is called a *current source* or *electric generator*.

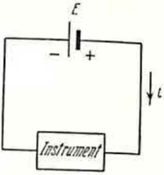


Fig. 38. Simple electric circuit.

An *electric circuit* is composed of a current source, connecting wires and instruments (or other devices) in which the current performs work (Fig. 38). Work in an electric circuit is performed by forces of a non-electrostatic nature which keep up a constant potential difference across the terminals of the source.

The *electromotive force* (e.m.f.) *of a source* of electric energy is defined as the work done in carrying unit electric charge around a closed circuit in which no current is flowing. The electromotive force is measured in the same units as the potential difference (for example, in volts).

Ohm's law for a section of a circuit which does not contain electromotive forces was established by experimental observation: *the current in a conductor is proportional to the potential* *difference between its ends*, i. e.,

$$i = \frac{U}{R}. \tag{4,26}$$

The constant of proportionality in this law $\frac{1}{R}$ is called the *conductance*. The quantity R is called the *resistance*; it depends on the "friction" which the charge carriers must overcome in their motion through the medium. Conductors in which current is due to the motion of free electrons are called *electronic conductors*.

The unit of resistance is the *ohm*. 1 ohm is the resistance of a conductor having a difference of potential between its ends equal to 1 volt when a current of 1 ampere flows through it.

The resistance of a wire conductor (of constant cross-section) is

$$R = \rho \frac{l}{S}, \tag{4,27}$$

where ρ is the *resistivity*, defined as the resistance of a conductor of unit length and unit cross-sectional area, l is the length of the conductor, and S—the cross-sectional area. The quantity $\sigma = \frac{1}{\rho}$ is called the *conductivity*. The unit of resistivity in the SI system is the ohm m. In electrical engineering l is expressed in m, the cross-sectional area S— in mm^2; hence ρ is expressed in ohm mm^2/m

$$1 \text{ ohm } \frac{\text{mm}^2}{\text{m}} = 10^6 \text{ ohm m}$$

The resistivity of most metals increases with the temperature. The dependence of the resistivity on the temperature can be represented approximately by the relation

$$\rho_t = \rho_0 (1 + \alpha t) \tag{4,28}$$

where ρ_t is the resistivity at the temperature t, ρ_0—the resistivity at 0° C, and α—the *temperature coefficient of resistivity*; this coefficient is numerically equal to the ratio of the change in resistivity caused by heating the conductor by 1° C to the initial resistivity. The resistivity of some metals at very low temperatures drops suddenly and becomes practically zero. This phenomenon is called *superconductivity*.

When resistors are connected *in series* the equivalent resistance R_Σ is equal to the sum of the separate resistances

$R_1, R_2, R_3, \ldots, R_n$:

$$R_\Sigma = R_1 + R_2 + R_3 + \ldots + R_n. \qquad (4,29)$$

For resistors connected *in parallel*:

$$\frac{1}{R_\Sigma} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}. \qquad (4,30)$$

Ohm's law for a section of a circuit containing e.m.f.. For a section of a circuit containing an e.m.f. the following relation, called *Ohm's law*, holds:

$$i = \frac{U + \mathscr{E}}{R}, \qquad (4,31)$$

where R is the resistance of the section, U—the potential difference between the ends of the section, and $\mathscr{E}$—the e.m.f.

It should be borne in mind that both $\mathscr{E}$ and U may be positive or negative. The e.m.f. is considered positive if it increases the potential in the direction of current flow (the current flows from the negative terminal to the positive terminal of the source); the potential difference is considered positive if the current inside the source flows in the direction of decreasing potential (from the positive to the negative terminal). For example, in charging an accumulator (Fig. 39) the charging current

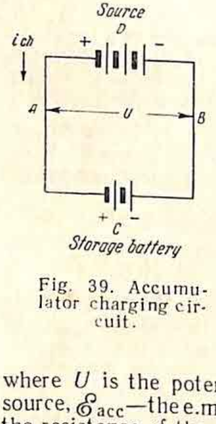


Fig. 39. Accumulator charging circuit.

$$i_{\text{ch}} = \frac{U - \mathscr{E}_{\text{acc}}}{R_{\text{acc}}},$$

where U is the potential difference across the terminals of the source, $\mathscr{E}_{\text{acc}}$—the e.m.f. of the accumulator being charged, R_{acc}—the resistance of the accumulator (the resistance of the connecting wires is neglected).

For the section of the circuit ADB we have in the same case

$$i_{\text{ch}} = \frac{\mathscr{E}_{\text{source}} - U}{R_{\text{source}}},$$

where $\mathscr{E}_{\text{source}}$ is the e.m.f. of the source, and R_{source}—its internal resistance.

For a closed unbranched circuit the relation (4,31) takes on the form (in this case $U=0$)

$$i=\frac{\mathscr{E}}{R}, \tag{4,32}$$

where R is the sum of the resistance of the external circuit and the internal resistance of the source.

Work of electric current. The work performed by an electric current in a section of a circuit is

$$A=iUt, \tag{4,33}$$

where t is the time of flow of the current, U—the potential difference across the section, and i—the current.

The work performed by a current which appears as a change in the internal energy of the conductor (heat) in the absence of an e.m.f. in the section of the circuit is

$$A=\frac{U^2}{R}t. \tag{4,34}$$

The work performed by a current which appears as a change in the internal energy of the conductor (regardless of whether the section of the circuit includes an e.m.f. or not) is

$$A=i^2Rt. \tag{4,35}$$

The unit of work (or energy) in the SI system is the *watt-second*, or *joule*, defined as the work performed when a direct current of 1 amp flows through a potential difference of 1 v in 1 sec. Another practical unit of work is the *kilowatt-hour* (kw-hr).

$$1\ \text{kw-hr}=3.6\times10^6\ \text{watt-sec}.$$

Kirchhoff's laws. The calculation of currents, potential differences and e.m.f.'s in complex circuits is carried out on the basis of Kirchhoff's laws.

First law: the algebraic sum of the currents flowing into a junction (or branch point) is zero. For example (Fig. 40),

$$i_1+i_2+i_3-i_4=0$$

Second law: the algebraic sum of the products of the currents by the respective resistances around a closed loop is equal to the algebraic sum of the e.m.f.'s in the loop.

To apply this law to a loop we consider those currents as positive whose direction coincides with an arbitrary direction around the loop. An e.m.f. is considered positive if the arbitrary direction around the loop coincides with the direction of the e.m.f. of the current source (the e.m.f. of a current source is directed from the negative terminal to the positive). For example (Fig. 41),

$$i_1R_1+i_2R_2-i_3R_3=\mathcal{E}_1+\mathcal{E}_2-\mathcal{E}_3.$$

For similar sources connected in series

$$i\,(nr_n+R)=n\mathcal{E}, \tag{4,36}$$

where n is the number of sources, r_n—the internal resistance of a source, R—the external resistance, $\mathcal{E}$—the e.m.f. of a source.

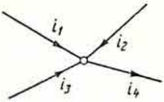


Fig. 40. Current junction

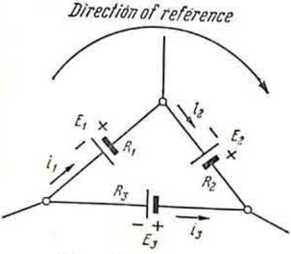


Fig. 41 Current loop.

For n similar sources connected in parallel

$$i\left(R+\frac{r_n}{n}\right)=\mathcal{E}. \tag{4,37}$$

2. Current in Electrolytes

Solutions of acids, bases and salts in water or in other solvents are called *electrolytes*. Molten salts are also characterised by electrolytic conductivity. The current in electrolytes is carried by ions which are formed when the substance passes into solution. *Ions* are positively or negatively charged parts of molecules.

The current density due to ions of both signs is

$$j=n_+ev_++n_-ev_-, \tag{4,38}$$

where n_+ is the concentration of positive ions, e—the charge of an ion, v_+—the drift velocity of the positive ions, n_-, v_-—the concentration and drift velocity of the negative ions.

The *mobility of the ions* is defined as the average drift velocity which an ion attains in a field of intensity 1 v/cm.

The current density can be expressed in terms of the ion mobilities u_+ and u_-:

$$j = (n_+ u_+ + n_- u_-) eE. \qquad (4,39)$$

Ohm's law holds for electrolytes. The decomposition of an electrolyte by an electric current is called *electrolysis.*

Faraday's first law. The mass of any substance liberated at the electrode in electrolysis is proportional to the total quantity of charge Q passing through the electrolyte:

$$m = KQ. \qquad (4,40)$$

The coefficient of proportionality K is called the *electrochemical equivalent* and is equal numerically to the mass of a given substance liberated when unit quantity of charge passes through the electrolyte.

Faraday's second law. The electrochemical equivalent of a given substance is proportional to its chemical equivalent:

$$K = C\frac{A}{Z}, \qquad (4,41)$$

where $\frac{A}{Z}$—the *chemical equivalent* is defined as the ratio of the atomic weight of an element to its valence. The constant C is the same for all substances and has the dimensions g/g-equiv.

The faraday. The same quantity of electric charge, equal in round numbers to 96,500 coulombs, when passed through a solution of an electrolyte, will liberate a mass of substance equal to the chemical equivalent of that substance. This quantity of electric charge is called the faraday:

$$C = 1/\mathrm{F}\ \text{g-equiv/coul}. \qquad (4,42)$$

Electrochemical cells. When a metal electrode is immersed in an electrolyte a potential difference is set up between the electrode and the solution. This potential difference is called the *electrochemical potential* of the given electrode in the given solution.

The *absolute normal potential* is called the value of the electrochemical potential of a metal in a solution with a normal concentration of ions (i. e., with a concentration of one gram-equivalent of ions per liter). Under such conditions the electrochemical potential depends only on the nature of the metal.

When two electrodes are immersed in an electrolyte a potential difference is set up between them, equal to the difference of their electrochemical potentials. An electrolyte with two different electrodes immersed in it is called an *electrochemical* *cell* (for example, a solution of sulfuric acid with a copper and a zinc plate immersed in it is called a *Voltaic cell*).

3. Current in Gases

The passage of electric current through a gas is due to the presence of ions and free electrons. Electrons may become detached from neutral gas molecules and some of them may attach themselves to other neutral molecules and atoms. This process is called *ionisation*. The work required to remove an electron from a molecule or atom is called the *ionisation potential* and is expressed in *electron-volts* (ev). An electron-volt is equal to the energy acquired by an electron in falling through a potential difference of 1 volt.

The current density in gases, as in metals and liquids, is determined by the concentration of the charge carriers (ions), their mobility and charge. However, in view of the fact that the ion concentration depends on the field intensity and varies throughout the volume of gas, Ohm's law does not apply, as a rule, to gaseous conductors.

Two kinds of conductivity are distinguished in gases: *induced conductivity*, when ionisation is caused by agents other than an electric field (for example, X-rays, heating, etc.); and *intrinsic conductivity*, when ionisation is due to the action of an electric field applied between the electrodes.

An electric current in vacuum (for example, in thermionic tubes) is due to the motion of electrons or ions which escape from electrodes placed in a vacuum.

In order to remove an electron from a metal work must be performed; this is known as the *work function*.

When a metal is heated it begins to emit electrons. This phenomenon is called *thermionic emission*. An electron can escape from the metal if the following condition is fulfilled:

$$\frac{1}{2} m v_n^2 \geqslant \varphi, \qquad (4,43)$$

where m is the mass of the electron, v_n—the projection of the thermal velocity of the electron on to the normal to the surface, and φ—the work function.

The maximum value of the thermionic current is called the *saturation current*. The density of the saturation current in thermionic emission is:

$$i_{\text{sat}} = A' T^2 e^{-\frac{\varphi}{kT}}, \qquad (4,44)$$

where A' is a constant which is different for different metals, T—the absolute temperature, k—Boltzmann's constant (see p. 61) and $e \cong 2.72$ is the base of the natural logarithms. The quantities A' and φ are sometimes called the *emission constants*.

According to the theory, A' should be the same for all pure metals (60.2 amp/cm^2 degree^2). Actually, however, it varies with different metals.

The so-called *oxide cathodes* have found wide application in practice. These cathodes are prepared by coating a metal base with barium oxide or an oxide of some other metal, which considerably decreases the work function.

Dielectric breakdown. When a large potential difference is applied to cold electrodes placed in a gas, a discharge in the form of a spark may take place. This phenomenon is called *breakdown*. The potential difference required to cause breakdown depends on the material, shape and dimensions of the electrodes, on the distance between them, and also on the nature and pressure of the gas.

In the case of large flat electrodes the breakdown potential for a given gas and electrode material depends only on the product pd (where p is the pressure of the gas, and d—the distance between the electrodes). In other words, if p and d are varied in such manner that their product remains constant, the breakdown potential will not change.

The distance between the electrodes at which breakdown occurs at a given potential difference is called the *spark gap*. The length of the spark gap is a measure of the potential difference between the electrodes.

4. Semiconductors

Semiconductors are substances whose electrical conductivity is due to the motion of bound electrons and whose resistivity at room temperature lies within the range from 10^{-2} to 10^9 ohms-cm. The resistivity of semiconductors is strongly temperature-dependent. In contradistinction to metals the resistivity of semiconductors decreases with an increase in the temperature. The resistivity of semiconductors depends strongly on the presence of impurities.

Electrons in matter are distributed about the atomic nuclei in such manner that any atom may possess only a discrete set of energy values. Every electron can occupy certain definite energy levels, which are different from the energy levels of other electrons. These energy levels are called *allowed* levels. The allowed energy levels fall into two regions, or bands, which are separated by the so-called *forbidden gap* containing the values of energy which are forbidden to the electron. At the temperature 0° K all the electrons are in the band of lowest energies, and all the energy levels in this band will be occupied (Fig. 42). This band is called the *valence band*. The second band (the *conduction band*) of the non-metallic elements does not contain a single electron at 0° K. In metals the conduction and the valence bands overlap.

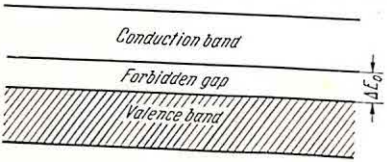


Fig. 42. Electron energy level diagram of semiconductor.

The energy required for an electron to pass from the valence band to the conduction band is called the *width of the forbidden gap* (ΔE_0). Semiconductors possess either electron (n-type) or hole (p-type) conductivity. *Electronic conductivity* is due to the motion of the electrons in the conduction band; *hole conductivity* is due to electrons in the valence band moving from one atom to another which has "lost" an electron to the conduction band. The motion of an electron in the valence band is equivalent to the motion of a positive charge in the opposite direction. Such a positive charge is termed a "hole".

5. Thermoelectricity

If a closed circuit is composed of two dissimilar metals and the junctions of the metals are maintained at different temperatures, a current will flow in the circuit. This current may be attributed to a *thermal e.m.f.* developed at the junctions, and the phenomenon itself is called the *thermoelectric effect*.

Within a certain temperature range the magnitude of the thermal e.m.f. is approximately proportional to the temperature difference. In this case

$$\mathscr{E}_T = \alpha (T_1 - T_2).$$

The quantity α is called the *differential* thermal e.m.f. (or the coefficient of the thermal e.m.f.); it is numerically equal to the thermal e.m.f. developed per degree centigrade.

TABLES AND GRAPHS

Electric Currents and the Earth's Atmosphere

The experimentally measured density of the vertical current i_{vert} (due to the motion of positive and negative ions in the atmosphere) is

$$i_{\text{vert}}\ 2.9\times10^{-6}\ \text{amp/cm}^2.$$

The density of the currents due to the motion of charged raindrops, snowflakes and hail is:

for light rain – 10^{-5} to 10^{-4} CGSE units of current/cm^2,

for thunderstorms and hail – up to 3×10^{-3} CGSE units of current/cm^2.

The current in a lightning stroke may be as high as 200,000 amp (the most common values are from 20,000 to 40,000 amp).

The potential in a lightning stroke may be as high as 10^9 v; the discharge lasts about 10^{-3} sec, its length can be about 10 km, and the diameter of the channel – up to 20 cm

Table 69

Resistivity and Temperature Coefficient of Resistivity of Metals

Metal	Resistivity at 20°C, ohm mm²/m	Temperature coefficient at 20°C
Aluminium	0.028	0.0049
Brass	0.025-0.06	0.002-0.007
Chromium	0.027	—
Copper	0.0175	0.0039
Iron	0.098	0.0062
Lead	0.221	0.0041
Mercury	0.958	0.0009
Molybdenum	0.057	0.0033
Nickel	0.100	0.0050
Phosphor bronze	0.015	0.0040
Silver	0.016	0.0036
Tantalum	0.155	0.0031
Tin	0.115	0.0042
Tungsten	0.055	0.0045
Zinc	0.059	0.0035

Note. The values given in the table are average values; for different samples they depend on the degree of purity, thermal treatment, etc.

The temperature coefficient of resistivity of pure metals is close to $1/273=0.00367$, i.e., to the value of the coefficient of thermal expansion of gases.

Table 70

Transition Temperatures to the Superconducting State for Some Metals

Substance	Transition temperature, °K
Metals	
Zirconium	0.3
Cadmium	0.6
Zinc	0.8
Aluminium	1.2
Uranium	1.3
Tin	3.7
Mercury	4.1
Tantalum	4.4
Lead	7.3
Niobium	9.2
Alloys	
Bi—Pt	0.16
Pb—Au	2.0-7.3
Sn—Zn	3.7
Pb—Hg	4.1-7.3
Sn—Hg	4.2
Pb—Ag	5.8-7.3
Pb—Sb	6.6
Pb—Ca	7.0
Compounds	
NiBi	4.2
PbSe	5.0
$SrBi_3$	5.5
NbB	6
MoC	7.6-8.3
Nb_2C	9.2
NbC	10.1-10.5
NbN	15-16
V_3Si	17.1
Nb_3Sn	18

Notes. 1. There are a number of superconducting alloys containing a greater number of components: Rose's metal (8 5°K), Newton's metal (8.5°K), Wood's metal (8.2°K). Pb—As—Bi (90°K), Pb—As—Bi—Sb (9.0°K).

2. Upon transition to the superconducting state the resistivity of compounds and alloys varies throughout a wide range of temperatures (sometimes as wide as 2°K). In addition the transition temperature depends on the heat treatment of the alloy or compound. In such cases the table indicates the bounds within which the transition temperature lies.

Table 71

Alloys of High Ohmic Resistance

Alloys	Resistivity at 20°C, ohm mm²/m	Temperature coefficient (in the range 0-100°C)	Maximum operating temperature, °C
Constantan (58.8 % Cu, 40% Ni, 1.2% Mn)	0.44-0.52	0.00001	500
Fechral (80% Fe, 14% Cr, 6% Al)	1.1-1.3	0.0001	900
German silver (65% Cu, 20% Zn, 15% Ni)	0.28-0.35	0.00004	150-200
Manganin (85% Cu, 12% Mn, 3% Ni)	0.42-0.48	0.00003	100
Nickeline (54% Cu, 20% Zn, 26% Ni)	0.39-0.45	0.00002	150-200
Nichrome (67.5% Ni, 15% Cr, 16% Fe, 1.5% Mn)	1.0-1.1	0.0002	1,000
Rheostan (84% Cu, 12% Mn, 4% Zn)	0.45-0.52	0.0004	150-200

Note The value of the temperature coefficient of resistance of constantan varies from −0.00004 to +0.00001 depending on the sample. The minus sign before the temperature coefficient denotes that the resistance decreases with increasing temperature.

Table 72

Allowed Current-Carrying Capacity of Insulated Wires for Prolonged Operation (amp)

Cross-sectional area, mm² / Material	1	1.5	2.5	4	6	10	16	25
Copper	11	14	20	25	31	43	75	100
Aluminium	8	11	16	20	24	34	60	80
Iron	—	—	8	10	12	17	30	—

Table 73

Resistivity of Electrolytes at 18° C and Different Concentrations (see Fig. 43)

Solute	Concentration, %	Resistivity, ohm cm	Temperature coefficient, χ (degree^{-1})
Ammonium chloride, NH_4Cl	5	10.9	0.0198
	10	5.6	0.0186
	20	3.8	0.0161
Copper sulfate, $CuSO_4$	5	52.9	0.0216
	10	31.5	0.0218
	17.5	23.8	0.0236
Hydrochloric acid, HCl	5	2.5	0.0158
	20	1.3	0.0154
	40	1.9	—
Nitric acid, HNO_3	10	2.1	0.0145
	20	1.5	0.0137
	30	1.3	0.0139
	40	1.4	0.0150
Sodium chloride, NaCl (common salt)	5	14.9	0.0217
	10	8.3	0.0214
	20	5.1	0.0716
Sodium hydroxide, NaOH	5	5.1	0.0201
	10	3.2	0.0217
	20	3.0	0.0299
	40	8.3	0.0648
Sulfuric acid, H_2SO_4	5	4.8	0.0121
	20	1.5	0.0145
	30	1.4	0.0162
	40	1.5	0.0178
Zinc sulfate, $ZnSO_4$	5	52.4	0.0225
	10	31.2	0.0223
	20	21.3	0.0243

Note. The resistivity of electrolyte falls off with increasing temperature (as distinct from metals). The resistivity for other temperatures ρ_t can be computed from the formula (compare with (4,28)): $\rho_t = \rho_{18}\,[1 - \chi\,(t - 18)]$, where χ is the temperature coefficient given in the table, ρ_{18} — the resistivity at 18°C, t — the temperature for which the resistivity ρ_t is sought.

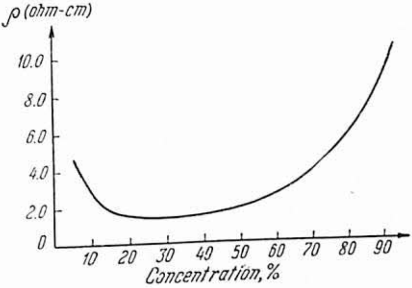


Fig 43. Concentration dependence of resistivity of aqueous solution of H_2SO_4 (18° C).

Table 74

Thermal Electromotive Force of Some Metal Couples in Millivolts

Junction temperature, °C	Platinum, platinum with 10% rhodium	Iron, constantan	Copper, constantan
−200	—	8	5.5
100	0.64	5	4
200	1.44	11	9
300	2.32	16	15
400	3.25	22	21
500	4.22	27	—
600	5.22	33	—
700	6.26	39	—
800	7.33	46	—
1,000	9.57	58	—
1,500	15.50	—	—

Note. The temperature of the reference junction is kept at 0° C.

Table 75

Differential Thermal e. m. f. (α) with Respect to Platinum at 0° C

Metal	α, μv/degree	Metal	α, μv/degree
Antimony	47.0	Copper	7.4
Bismuth	−65.0	Iron	16.0
Constantan	−34.4	Nickel	−16.4

Note. The minus signs indicate that the current in the hot junction flows from the metal with the smaller algebraic value of α. For example, in the thermocouple copper-constantan (Fig. 44) the current in the hot junction flows from constantan to copper.

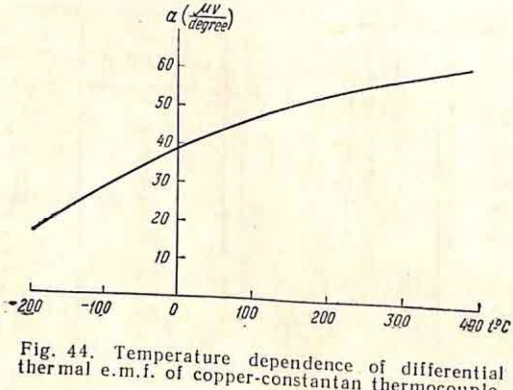


Fig. 44. Temperature dependence of differential thermal e.m.f. of copper-constantan thermocouple.

Table 76

Electrochemical Equivalents

Ion	Gram chemical equivalent	K, mg/coul	Ion	Gram chemical equivalent	K, mg/coul
H^{+}	1.008	0.0104	CO_3^{--}	30.0	0.3108
O^{--}	8.0	0.0829	Cu^{++}	31.8	0.3297
Al^{+++}	9.0	0.0936	Zn^{++}	32.7	0.3387
OH^{-}	17.0	0.1762	Cl^{-}	35.5	0.3672
Fe^{+++}	18.6	0.1930	SO_4^{--}	48.0	0.4975
Ca^{++}	20.1	0.2077	NO_3^{-}	62.0	0.642
Na^{+}	23.0	0.2388	Cu^{+}	63.6	0.6590
Fe^{++}	27.8	0.2895	Ag^{+}	107.9	1.118

Note. The number of plus or minus signs in the superscript denotes the number of elementary charges carried by one ion.

Table 77

Absolute Normal Potentials of Some Metals

Metal	Normal potential, v	Metal	Normal potential, v
Cadmium	−0.13	Manganese	−0.78
Chromium	−0.29	Mercury	1.13
Copper	0.61	Nickel	0.04
Iron	−0.17	Silver	1.07
Lead	0.15	Zinc	−0.50

Table 78

E.m.f. of Electrochemical Cells

Name of cell	Negative electrode	Positive electrode	Solution	e.m.f., v
Daniell	Zinc	Copper	Different solutions at electrodes: zinc immersed in solution of sulfuric acid (5-10%); copper immersed in saturated solution of copper sulfate $CuSO_4$	1.1
Edison	Powdered iron (or cadmium mixed with iron oxides)	Nickel dioxide	20% solution of potassium hydroxide (KOH)	1.4-1.1
Grenet	Zinc	Carbon	12 parts $K_2Cr_2O_7$, 25 parts H_2SO_4, 100 parts H_2O	2.01
Lead accumulator	Spongy lead	Lead peroxide PbO_2	27-28% solution of H_2SO_4, free from chlorine, density 1.20	2.0-1.9 at 15° C
Leclanche	Zinc	Carbon	Solution of sal-ammoniac, manganese peroxide with powdered carbon	1.46
Leclanche (dry)	Zinc	Carbon	1 part ZnO, 1 part NH_4Cl, 3 parts gypsum, 2 parts $ZnCl_2$ and water until a paste is formed	1.3
Silver-zinc accumulator	Zinc oxide	Silver	Solution of potassium hydroxide (KOH)	1.5
Weston, normal	Cadmium amalgam	Mercury	Saturated solution of $CdSO_4$, paste of Hg_2SO_4 and $CdSO_4$	1.0183

Charging and Discharging Accumulators

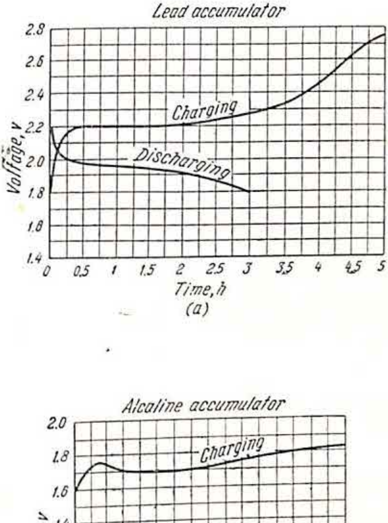


Fig. 45. Variation of voltage of accumulator during charging and discharging: *a*) lead accumulator, *b*) Edison storage cell.

Table 79

Mobility of Ions in Aqueous Solutions at 18°C

Cations	Mobility cm²/sec v	Anions	Mobility, cm²/sec v
H^+	0.003263	OH^-	0.00180
K^+	0.000669	Cl^-	0.00068
Na^+	0.000450	NO_3^-	0.00062
Ag^+	0.00056	SO_4^{--}	0.00068
Zn^{++}	0.00048	CO_3^{--}	0.00062
Fe^{+++}	0.00046		

Notes. 1. Cations are positively charged, anions — negatively charged ions.

2. The ionic mobility increases approximately 2% per 1°C increase in temperature.

3. The number of plus or minus signs in the superscripts indicates the number of elementary charges carried by one ion.

Table 80

Mobility of Electrons in Metals (in cm²/sec v)

Metal	Ag	Na	Be	Cu	Au	Li	Al	Cd	Zn
Mobility	56	48	44	35	30	19	10	7.9	5.8

Note. The field intensity inside metals actually does not exceed 0.001 v/cm; hence, the electron velocities will be numerically much smaller than the values of the mobility given in the table. This can easily be verified by means of the relation (4,23) by inserting the permissible values of the current density given in Table 72

Table 81

Mobility of Ions in Gases at 760 mm Hg and 20°C (in $cm^2/sec\ v$)

Gas	Positive ion mobility	Negative ion mobility
Air, dry	1.36	1.87
Air, saturated with water vapour	1.4	2.1
Argon	1.5	1.70
Carbon dioxide	0.76	0.81
Helium	16.0	—
Hydrogen	6.3	8.1
Oxygen	1.36	1.8

Notes. 1. The values of the mobility are given for the case of ionisation by X-rays.

2. The mobility of ions in gases decreases with a rise in pressure and increases with the temperature.

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Table 82

Ionisation Potentials (in Electron-Volts)

Ionisation process	Ionisation potential	Ionisation process	Ionisation potential
$He \rightarrow He^+$	24.5	$H \rightarrow H^+$	13.5
$Ne \rightarrow Ne^+$	21.5	$O \rightarrow O^+$	13.5
$N_2 \rightarrow N_2^+$	15.8	$H_2O \rightarrow H_2O^+$	13.2
$Ar \rightarrow Ar^+$	15.7	$Xe \rightarrow Xe^+$	12.8
$H_2 \rightarrow H_2^+$	15.4	$O_2 \rightarrow O_2^+$	12.5
$N \rightarrow N^+$	14.5	$Hg \rightarrow Hg^+$	10.4
$CO_2 \rightarrow CO_2^+$	14.4	$Na \rightarrow Na^+$	5.1
$Kr \rightarrow Kr^+$	13.9	$K \rightarrow K^+$	4.3

Table 83

Emission Constants of Some Metals and Semiconductors

Element	φ, ev	A', $\frac{\text{amp}}{\text{cm}^2\,\text{degree}^2}$	Element	φ, ev	A', $\frac{\text{amp}}{\text{cm}^2\,\text{degree}^2}$
Aluminium .	3.74	—	Nickel . . .	4.84	30
Antimony . .	2.35	—	Platinum . .	5.29	32
Barium . . .	2.29	—	Selenium . .	4.72	—
Cesium . . .	1.89	160	Silicon . . .	4.10	—
Chromium . .	4.51	48	Tellurium . .	4.12	—
Copper . . .	4.47	65	Thorium . . .	3.41	70
Germanium .	4.56	—	Tin	4.11	—
Iron	4.36	26	Tungsten . .	4.50	60-100
Molybdenum	4.27	115	Uranium . . .	3.74	—

Note. The work function depends markedly on the cleanliness of the surface and on impurities. The figures in the table are for pure specimens.

Table 84

Emission Constants of Films on Metals

Element	Film	φ, ev	A', $\frac{\text{amp}}{\text{cm}^2\,\text{degree}^2}$
Tungsten	Barium	1.56	1.5
"	Thorium	2.63	3.0
"	Uranium	2.84	3.2
"	Cesium	1.36	3.2
"	Zirconium	3.14	5.0
Molybdenum	Thorium	2.58	1.5
Tantalum	"	2.52	0.5

Table 85

Emission Constants of Oxide-Coated Cathodes

Cathode	φ, ev	A', $\frac{\text{amp}}{\text{cm}^2\,\text{degree}^2}$
Barium on oxidised tungsten	1.10	0.3
Nickel — BaO — SrO	1.20	0.96
Barium — oxygen — tungsten	1.34	0.18
Pt — Ni; BaO — SrO . . .	1.37	2.45
BaO on a nickel alloy . . .	1.50-1.83	0.087-2.18
Thorium oxide-coated cathode (mean value)	2.59	4.35

Table 86

Properties of Most Important Semiconductors

(see also Figs. 46-49)

Substance	Melting point, °C	Width of forbidden gap, ev	Electron mobility, cm²/sec v	Hole mobility, cm²/sec v
B	2,300	1.1	10	10
C — graphite	—	0.1	—	—
C — diamond	—	6-7	1,800	1,200
Si	1,414	1.12	1,900	500
Ge	958	0.75	3,900	1,900
Sn, gray	—	0.08	3,000	—
S	113	2.4	—	—
Se, gray	220	2.3	—	—
Te	452	0.36	1,700	1,200
I	113.5	1.3	25	—
Ag_2Te	955	0.17	4,000	—
HgTe	670	0.2	10,000	100
B_2Te_3	585	0.25	600	150
Mg_2Sn	778	0.36	200	150
PbSe	1,065	0.5	1,400	1,400
ZnTe	1,240	0.6	100	—
PbS	1,114	1.2	650	800
AgBr	430	1.35	35	—
CdTe	1,045	1.45	450	100
Cu_2O	1,232	1.5-1.8	—	100
Al_2O_3	2,050	2.5	—	—
ZnO	1,975	3.2	200	—

Notes. 1. The values of the mobilities are given for room temperature and field intensities less than the critical field.

Deviations from Ohm's law may occur, due to the field-dependence of the mobility. The least intensity for which such deviations are observed is called the *critical field* (E_{cr}). At $t=20°C$ the critical field in

n-type germanium	$E_{cr}=900$ v/cm
p-type germanium	$E_{cr}=1,400$ v/cm
n-type silicon	$E_{cr}=2,500$ v/cm
p-type silicon	$E_{cr}=7,500$ v/cm

The critical field decreases with decreasing temperature.

2. The width of the forbidden gap in metals is of the order of 0.1 ev; in dielectrics — over 10 ev.

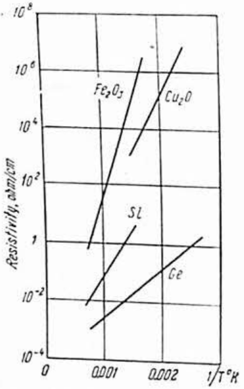

Fig. 46. Dependence of resistivity ρ on $1/T$ for intrinsic semiconductor, the values of ρ are plotted on the ordinate axis on a logarithmic scale.

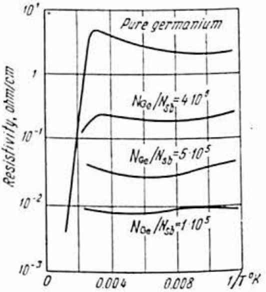

Fig. 47. Temperature dependence of resistivity of germanium. The values of the resistivity are plotted on the ordinate axis on a logarithmic scale, the reciprocal of the absolute temperature—on the axis of abscissae, N_{Ge}—number of germanium atoms, N_{Sb}—number of antimony atoms.

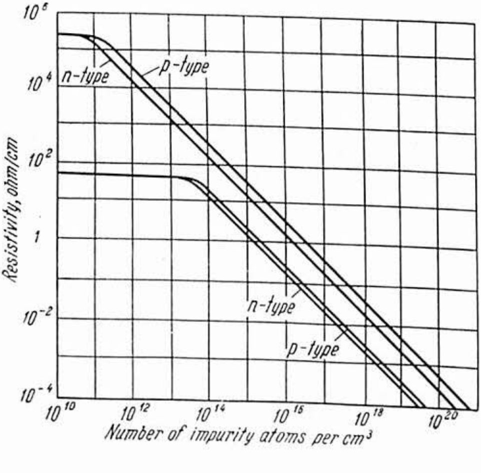

Fig. 48. Dependence of resistivity of germanium (lower curves) and silicon (upper curves) on concentration of impurity atoms. Temperature—about 20° C.

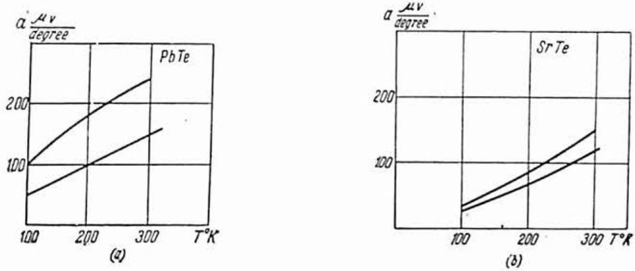

Fig. 49. Differential thermal e.m.f. versus temperature: *a*) lead telluride (upper curve—concentration of impurity atoms $3.5\times10^{18}\text{cm}^{-3}$, lower curve—$0.5\times10^{18}\text{cm}^{-3}$), *b*) antimony telluride (upper curve—concentration of impurity atoms $5.5\times10^{18}\text{cm}^{-3}$, lower curve—$3.5\times10^{18}\ \text{cm}^{-3}$).

Table 87

Spark Gaps for Air at 760 mm Hg (in mm)

Form of electrodes Potential difference, v	Two pointed wires	Two spheres of diameter 5 cm	Two plates
20,000	15.5	5.8	6.1
40,000	45.5	13	13.7
100,000	220	45	36.7
200,000	410	262	75.3
300,000	600	530	114

C. ELECTROMAGNETISM

FUNDAMENTAL CONCEPTS AND LAWS

1. The Magnetic Field. Magnetic Induction

If a freely pivoted magnetic needle is placed near a wire carrying current, the needle will be deflected (will be oriented in a certain direction). The forces causing this deflection are called *magnetic* forces.

A region of space in which magnetic forces act is called a *magnetic field*.

A magnetic field does not act upon electric charges at rest.

The *direction of the magnetic field* is defined as the direction of the force acting on the north pole of a magnetic needle placed at the given point of the field.

The force acting on a wire carrying current in a magnetic field is determined by Ampère's law:

$$F = ilB \sin \beta, \tag{4,45}$$

where l is the length of the wire, β — the angle between the direction of the magnetic field and the current in the wire; i, and B are expressed in the same system of units.

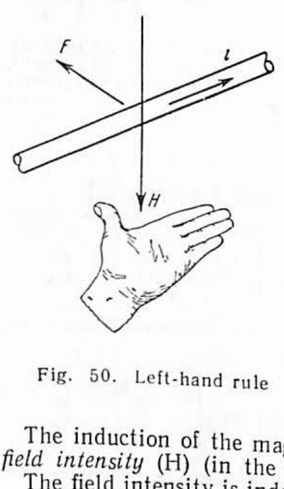

Fig. 50. Left-hand rule

The quantity B in equation (4,45) characterises the magnitude and direction of the magnetic field and is called the *magnetic induction*.

The magnetic induction is numerically equal to the force which the magnetic field exerts upon a unit current carrying element ($il = 1$) situated perpendicular to the field.

The magnetic induction is a vector quantity. Its direction coincides with the direction of the magnetic field. The magnetic induction depends on the properties of the medium.

The induction of the magnetic field in vacuum is called the *field intensity* (H) (in the CGSM system).

The field intensity is independent of the properties of the medium; it is determined by the current and the shape of the conductor.

The quantity $\mu = \frac{B}{H}$ characterises the magnetic properties of the medium and is called the *permeability of the medium*.

The direction of the force acting on a current-carrying conductor is determined by means of the *left-hand rule*: if the open palm of the left hand is placed so that the lines of force of the magnetic field enter the palm, while the outstretched fingers point in the direction of the current, then the thumb will indicate the direction of the force acting on the conductor (Fig. 50).

Two sufficiently long straight parallel conductors of the same length l carrying currents i_1 and i_2, respectively, interact with a force

$$F=\frac{2\mu i_1 i_2 l}{a}, \text{ (CGSM)} \qquad (4,46)$$

$$F=\frac{i_1 i_2 \mu_0 \mu}{2\pi a}$$

where a is the distance between the conductors and μ is the permeability of the medium, and μ_0—the permeability of vacuum.

Currents flowing in the same direction attract, currents flowing in opposite directions repel each other.

The force acting on a moving charge in a magnetic field (called *Lorentz' force*) is

$$F_L = evB \sin\alpha, \qquad (4,47)$$

where e is the charge, v—the velocity and α—the angle between the direction of the velocity and the induction B. The Lorentz force is directed perpendicular to the plane determined by the vectors B and v.

2. CGSM and SI Systems of Units

In the CGS electromagnetic (CGSM) system the fundamental units are the *centimetre*, *gram* (mass), *second*, and for electric quantities—the permeability. The permeability of vacuum ($\mu_0=1$) is taken as the unit of permeability. The unit of current in this system is derived from the law of interaction of currents (4,46).

The unit of current in the CGSM system is defined as such a direct current which, when flowing through two infinitely long parallel wires placed in vacuum 1 cm apart, causes them to interact with a force of 2 dynes per cm of their length. It is assumed that both wires have a sufficiently small cross-sectional area.

The fundamental units of the SI system are the *meter*, *kilogram* (mass), *second* and the unit of current—*ampere*.

An *ampere* is defined as such a direct current which when flowing through two infinitely long parallel wires placed in vacuum at a distance of one *meter* causes them to interact with a force of 2×10^{-7} SI units of force per *meter* of their length.

In this system the permeability is a derived quantity. For vacuum

$$\mu_0 = 4\pi\times10^{-7} \text{ henry/meter}.$$

The unit of magnetic field intensity in the CGSM system is the *oersted*; in the SI system—the ampere per meter, (amp/m).

A gauss is defined as the induction of a magnetic field which acts on 1 cm of a straight conductor carrying 1 CGSM unit of current with a force of 1 dyne.

The unit of magnetic induction in the CGSM system is the *gauss*; in the SI system—the *weber per square meter* (weber/m^2).

3. Intensity of the Magnetic Fields of Currents

The *lines of force of a magnetic field* are defined as curves, the tangents to which coincide in direction with the intensity at each point. The magnetic lines of force are closed curves (as distinct from the lines of force of an electrostatic field); such fields are called *vortical* fields. The lines of force of a straight current-carrying conductor are concentric circles lying in a plane perpendicular to the current (Fig. 51). The direction of the magnetic lines of force is determined by the *right-hand rule*. If the thumb of the right hand is placed along the wire pointing in the direction of the current, the curled fingers of the right hand will point in the direction of the magnetic lines of force (Figs. 51, 52 and 53).

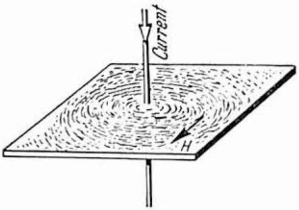

Fig. 51. Magnetic lines of force of a straight wire carrying current, pattern formed by iron filings.

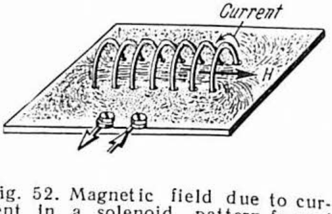

Fig. 52. Magnetic field due to current in a solenoid, pattern formed by iron filings.

The intensity of the magnetic field* generated by an element of conductor of length Δl carrying a current i is (Fig. 53)

$$\Delta H = \frac{i\Delta l \sin\alpha}{r^2}, \tag{4,48}$$

---

* The following formulas are written in the CGSM system, unless otherwise specified.

where r is the distance from the element Δl to the point for which the intensity is sought, α—the angle between Δl and r. This relation is called Biot and Savart's law.

The magnetic field intensity of a long straight current-carrying wire is

$$H=\frac{2i}{a}, \qquad (4{,}49)$$

where a is the distance from the wire to the point at which the intensity is sought.

The magnetic field intensity at the centre of a circular loop of current-carrying wire is

$$H=\frac{2\pi i}{R}, \qquad (4{,}50)$$

where R is the radius of the loop.

The magnetic field intensity inside a toroid (Fig. 54) is

$$H=\frac{2Ni}{r}, \qquad (4{,}51)$$

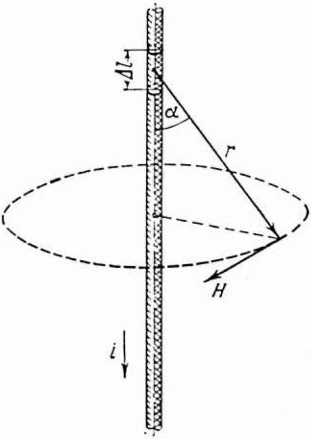

Fig. 53. Illustration of Biot and Savart's law.

where N is the total number of turns of wire, r—the radius of the toroid.

The field intensity inside a straight solenoid, whose length considerably exceeds the diameter of a turn is

$$H=4\pi ni, \qquad (4{,}52)$$

where n is the number of turns per cm of the length of the solenoid. In such a solenoid the field intensity is the same in magnitude and direction at all points, i. e., the field is homogeneous.

In electrical engineering the product ni for a solenoid is called the number of *ampere-turns* per centimeter.

1 oersted $=1/0.4\pi$ ampere-turns/cm ≈ 1 ampere-turn/cm.

The field intensity of a moving charged particle (Fig. 55) is

$$H=\frac{ev\sin\vartheta}{r^2}, \qquad (4{,}53)$$

where v is the velocity of the particle, r—the distance from the

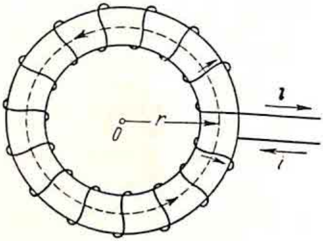

Fig. 54. Toroid.

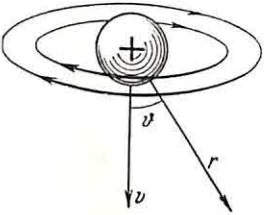

Fig. 55. Magnetic field of moving charge.

particle to the point of interest, ϑ—the angle between the direction of the velocity and the line drawn from the particle to the given point of the field.

4. Work Performed in the Motion of a Current-Carrying Wire in a Magnetic Field. Electromagnetic Induction

When a current-carrying wire moves through a magnetic field work is performed:

$$A = i\,(\Phi_2 - \Phi_1), \tag{4,54}$$

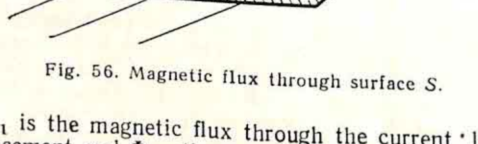

Fig. 56. Magnetic flux through surface S.

where Φ_1 is the magnetic flux through the current loop prior to displacement and Φ_2—the magnetic flux after displacement.

The magnetic flux through a loop (in a homogeneous field) is defined as the product of the magnetic induction by the area of the loop and the cosine of the angle between the direction of the field and the normal to the area of the loop (Fig. 56)

$$\Phi = BS\cos\alpha. \tag{4,55}$$

The unit of magnetic flux in the CGSM system is the *maxwell*, in the SI system—the *weber*.

When the magnetic flux through a circuit is changed an electric current is induced in the circuit. This phenomenon is called *electromagnetic induction*, and the current thus generated is called an *induced current*.

The direction of the induced current is always such that the magnetic field of the current opposes the change in flux which caused the induced current (Lenz' law).

The magnitude of the induced electromotive force is given by the formula

$$\mathcal{E}=-\frac{\Delta\Phi}{\Delta t}. \tag{4,56}$$

In other words, the induced e.m.f. is equal to the time rate of change of the magnetic flux through the loop. The negative sign indicates the direction of the e.m.f. (in accordance with Lenz' law).

5. Self-Induction

Any change in the current in a conductor leads to the appearance of an induced e.m.f., due to the magnetic flux of the current. This phenomenon is called *self-induction*.

The self-induced e.m.f. can be computed by the formula:

$$\mathcal{E}_s=-L\frac{\Delta i}{\Delta t}, \tag{4,57}$$

where L is the self-inductance, $\frac{\Delta i}{\Delta t}$—the rate of change of the current. L depends on the geometrical shape and dimensions of the conductor and on the properties of the medium.

The unit of inductance in the SI system is the *henry*, in the CGSM system—the centimeter.

A *henry* is defined as the inductance of a conductor in which a change of current of 1 ampere per second induces an e.m.f. of 1 volt,

$$1\ \text{henry}=10^9\ \text{cm}.$$

The inductance of a solenoid with a core is

$$L=k\,\frac{4\pi\mu N^2S}{l}\ (\text{cm}), \tag{4,58}$$

where μ is the permeability, S—the cross-sectional area of the solenoid, l—the length of the wire, k—a coefficient depending on the ratio of the length of the wire to the diameter of the coil (l/d). Table 96 gives values of k. It should be observed that when L is computed using formula (4,58), the quantity μ for ferromagnetic materials will depend on the shape of the core.

The inductance of a coaxial cable of length l is

$$L=2\mu l \ln \frac{R_2}{R_1} \text{ (cm)}, \tag{4,59}$$

where R_2 and R_1 are the radii of the external and internal cylinders.

The inductance of a two-wire line of length l and radius of the wires r (for $r \ll a$) is

$$L=4\mu l \ln \frac{a}{r} \text{ (cm)}, \tag{4,60}$$

where a is the distance between the axes of the wires.

The energy of the magnetic field of a conductor carrying current is

$$W=\frac{1}{2} Li^2. \tag{4,61}$$

The region of space in which a magnetic field exists contains stored energy. The energy density of a homogeneous magnetic field (the energy per unit volume) can be computed by the formula:

$$w=\frac{\mu H^{2}\,*}{8\pi}. \tag{4,62}$$

The lifting power of an electromagnet is given by

$$F=\frac{B^2 S}{\mu_0 8\pi}, \tag{4,63}$$

where S is the cross-sectional area of the pole-piece of the magnet, and μ_0—the permeability of air.

Eddy currents are induced currents in massive conductors placed in a variable magnetic field.

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* See footnote on p. 102.

6. Magnetic Properties of Matter

Magnetic materials are materials in which a state of magnetisation can be induced. When such materials are magnetised they create a magnetic field in the surrounding space.

The degree of magnetisation of a magnetic material is characterised by the *magnetisation vector* I which is proportional to the field intensity generated by the material.

The magnetic induction B is a vector quantity which is equal to the average value of the induction inside the material. This quantity is composed of the induction due to the field of the magnetising current ($\mu_0 H$) and the induction due to the field of the magnetic material ($4\pi I$):

$$B = \mu_0 H + 4\pi I, \text{ (CGSM)} \tag{4,64}$$

where μ_0 is the permeability of vacuum.

The magnetisation vector and the intensity of the magnetising field are connected by the formula:

$$I = \chi H, \tag{4,65}$$

where the quantity χ, called the *magnetic susceptibility*, depends on the nature of the magnetic material and on its state (temperature, etc.).

Since $B = \mu H$, then

$$\mu = \mu_0 + 4\pi\chi. \quad \text{(CGSM)} \tag{4,66}$$

Materials for which $\mu > 1$ (but small!) are called *paramagnetic*; if $\mu < 1$ the material is called *diamagnetic*. Materials for which μ is much greater than unity are called *ferromagnetic*. Ferromagnetic materials are crystalline.

Ferromagnetic and paramagnetic materials differ in a number of their properties.

a) The *magnetisation curve*, which expresses the relation between H and B, is a straight line for paramagnetic materials, but it is an intricate curve for ferromagnetic materials. This means that μ is a constant for paramagnetic materials, while for ferromagnetic materials it depends on the field intensity.

b) The magnetic susceptibility of ferromagnetic materials varies with the temperature in a more complicated manner; at a certain temperature T_c called the *Curie temperature* (*Curie* *point*) the ferromagnetic properties disappear: the ferromagnetic substance becomes paramagnetic.

c) The magnetisation of a ferromagnetic material depends, in addition to the field intensity, on the magnetic history of the sample: the value of the induction lags behind that of the field intensity. This phenomenon is called *hysteresis*, and the curve depicting the dependence of B on H in the process of remagnetisation (Fig. 57) is called a *hysteresis loop*.

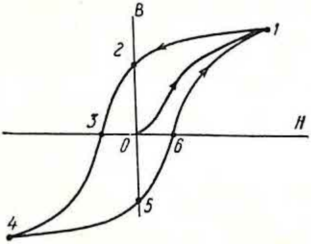


Fig. 57. Hysteresis loop: *01* — curve of magnetisation from unmagnetised state, *123* — demagnetisation curve.

The value of the residual magnetic induction of the ferromagnetic material after the magnetising field has been reduced to zero ($H=0$) is called the *retentivity* (B_r).

The *coercive force* (H_r) is the value of the magnetic field intensity needed to reduce the residual induction to zero (the direction of this field must be opposite to that of the retentivity).

The *saturation value* (I_s) is the greatest value of the magnetisation I. When a ferromagnetic material has been magnetised to the saturation value, further increase of the field intensity will have practically no effect on the magnetisation. The magnetic saturation is measured in *gausses*.

The *initial permeability* (μ_0) is the limiting value of the permeability, when the intensity and the induction tend to zero, i. e.,

$$\mu_0 = \lim_{H \to 0} \mu.$$

The properties of ferromagnetic materials are explained by means of the domain theory of magnetisation. According to this theory, in the absence of an external magnetic field a ferromagnetic material is composed of many small regions or *domains* each magnetised to saturation. In the absence of an external field the directions of magnetisation of these domains are distributed in such a way that the total magnetisation of the specimen is zero.

When a ferromagnetic material is placed in a magnetic field the domain boundaries are displaced (in weak fields) and the direction of magnetisation of the domains rotates towards the direction of the magnetising field, as a result of which the material becomes magnetised.

TABLES AND GRAPHS

Magnetic Field of the Earth

The earth is surrounded by a magnetic field. The curve drawn through the points of the earth's surface at which the intensity is directed horizontally is called the *magnetic equator*.

The points of the earth at which the intensity is directed vertically are called the *magnetic poles*. There are two such points: the north magnetic pole (in the southern hemisphere) and the south magnetic pole (in the northern hemisphere).

The magnetic field intensity at the magnetic equator is about 0.34 oersted; at the magnetic poles it is about 0.66 oersted. In some places (the regions of the so-called magnetic anomalies) the intensity increases sharply In the region of the Kursk magnetic anomaly it is 2 oersteds.

Table 88

Properties of Some Steels Used in Electrical Engineering

Steel	Initial permeability, gauss/oersted	Maximum permeability, gauss/oersted	Coercive force, oersted	Induction at 25 oersteds, gauss	Electric resistivity, ohm mm²/m
Э 31	250	5,500	0.55	15,200	0.52
Э 41	300	6,000	0.45	14,900	0.6
Э 42	400	7,500	0.4	14,900	0.6
Э 45	600	10,000	0.25	14,600	0.62
Э 310	1,000	30,000	0.12	17,800	0.5

Table 89

Properties of Some Iron-Nickel Alloys

These alloys have a high permeability, which decreases sharply at high field intensities and high frequencies, and in addition, depends strongly on mechanical strains.

Alloy	Initial permeability, gauss/oersted	Maximum permeability, gauss/oersted	Coercive force, oersted	Saturation value of magnetisation, gauss
Chromium-permalloy (H80×C)	3,000	150,000	0.015	6,500
Giperom 50	3,400	28,000	0.06	—
Giperom 766	14,000	45,000	0.04	—
Iron, technically pure	200	5,000	1.0	21,500
Molybdenum-permalloy (4% Mo)	2,000	120,000	0.02	8,500
Permendur	800	4,500	2.0	24,000
Silicon iron	450	8,000	0.4-0.6	20,000
Superpermalloy (5% Mo)	100,000	800,000	0.004	7,500

Table 90

Properties of Some Magnetically Refractive Materials

These materials are characterised by a high coercive force, and are used in the manufacture of permanent magnets. The maximum value of the quantity $\frac{HB}{8\pi}$ is an important characteristic. This quantity is proportional to the maximum energy of the magnetic field surrounding the ferromagnetic material.

Magnet material	Coercive force, oersted	Retentivity, gauss	Maximum value of quantity $HB/8\pi$, erg/cm^3
Alloys: alni	550	5,500	52,000
„ alnico	500	7,000	61,000
„ alnisi	800	4,000	56,000
„ magnico	550	12,000	190,000
Chromium steel ЭЕХ3А	60	9,000	11,000
Cobalt steel ЭЕК3О	220	9,000	37,000
Molybdenum steel	65	10,000	—
Platinum alloys	1,500-2,700	4,500-5,800	—
Tungsten steel ЭЕВА	60	10,000	12,000

Table 91

Properties of Magneto-Dielectrics

Magneto-dielectrics (and ferrites) are materials possessing both a relatively high magnetic permeability and a high electric resistivity.

Material	μ, gauss/oersted	Maximum operating frequency, Mc/sec
Alsifer РЧ-6	5-6	50
" РЧ-9	9-10	2-3
" ФИ 25	20-24	1
Carbonyl iron	11	30-50
Magnetite	6-9	5-10

Table 92

Principal Properties of Ferrites

Ferrites are mixtures of metals (nickel, zinc, iron) subjected to special heat treatment, as a result of which they acquire a high resistivity.

Ferrite	μ, gauss/oersted	Maximum operating temperature, °C	B_{max}, gauss
Ferrocart-2,000-I	2,000	55	2,500
Ferrocart-2,000-II	2,000	70	2,500
Ferrocart-1,000	1,000	110	3,200
Ferrocart-600	600	120	3,100
Ferrocart-500	500	120	2,800
Ferrocart-400	400	120	2,300
Ferrocart-200	200	120	1,800
Ferrocart И-4	200	250	4,200
Ferrocart И-5	150	360	4,800
Ferrocart Р4-15	15	400	1,850
Ferrocart Р4-10	10	400	1,400

Table 93

Permeability (μ) of Paramagnetic and Diamagnetic Materials in CGSM Units

Paramagnetic material	$(\mu-1)\times10^6$	Diamagnetic material	$(1-\mu)\times10^6$
Air	0.38	Benzene	7.5
Aluminium	23	Bismuth	176
Ebonite	14	Copper	10.3
Liquid oxygen . .	3,400	Glass	12.6
Nitrogen	0.013	Hydrogen	0.063
Oxygen	1.9	Quartz	15.1
Platinum	360	Rock salt	12.6
Tungsten	176	Water	9.0

Table 94

Curie Points of Metals

Substance	T_C, °C	Substance	T_C, °C
Gadolinium	20	Magnetite	585
Permalloy, 30% . . .	70	Iron, electrolytic . .	769
Heusler alloy	200	Iron, resmelted in hydrogen	774
Nickel	358	Cobalt	1,140
Permalloy, 78% . . .	550		

Table 95

Specific Magnetic Susceptibility (per gram) of Some Metals at 18°C in CGSM Units

The specific susceptibility χ_{sp} is equal to the ratio of the susceptibility χ to the density of the material ρ: $\chi_{sp}=\frac{\chi}{\rho}$.

Metal	$\chi_{sp}\times10^6$	Metal	$\chi_{sp}\times10^6$
Aluminium	0.58	Manganese	7.5
Antimony	−0.87	Mercury	−0.19
Cadmium	−0.18	Selenium	−0.32
Calcium	0.5	Silver	−0.20
Chromium	3.6	Sodium	0.6
Copper	−0.086	Tellurium	−0.31
Germanium	−0.12	Tin	0.03
Indium	−0.11	Tungsten	0.28
Lead	−0.12	Vanadium	1.4
Lithium	0.5	Zinc	−0.157

Dependence of Magnetic Permeability and Induction on the Magnetic Field Intensity

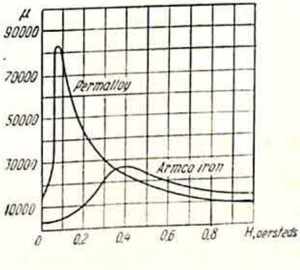


Fig. 58. Dependence of permeability of iron and permalloy on the intensity in weak fields.

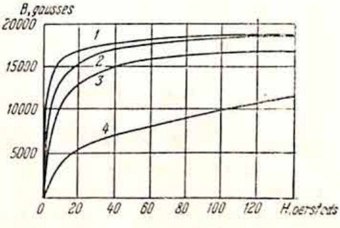


Fig. 59. Dependence of induction on intensity (curve 1 – electrolytic iron; curve 2 – low-carbon steel, curve 3 – cast steel; curve 4 – cast iron).

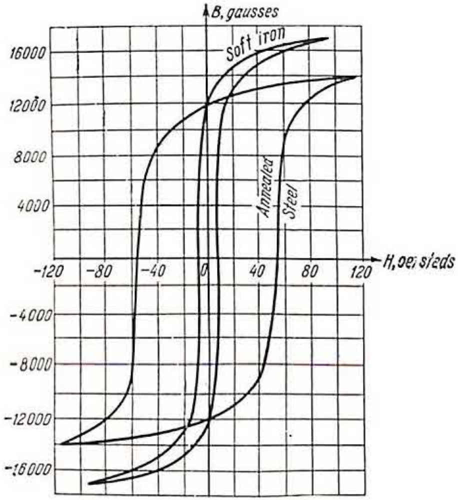


Fig. 60. Hysteresis loop for soft iron and tempered steel.

Table 96

Values of Coefficient *k* for Calculating Inductance

Ratio of length of winding to diameter (l/d)	0.1	0.5	1	5	10
k	0.2	0.5	0.6	0.9	~1.0

Note. For $l/d \geqslant 10$ k is close to unity.

D. ALTERNATING CURRENTS

FUNDAMENTAL CONCEPTS AND LAWS

An *alternating current* is one which periodically reverses its direction.

A current which varies periodically only in magnitude is called a *pulsating direct current*.

In practice most frequent use is made of alternating currents which vary sinusoidally (Fig. 61). Periodic currents which vary otherwise than sinusoidally can be represented to any degree of approximation by a sum of sinusoidal alternating currents (see p. 77).

The instantaneous values of a sinusoidal alternating current and voltage are given by the formulas:

$$i = I_m \sin \omega t, \qquad (4,67)$$

$$u = U_m \sin(\omega t + \varphi), \qquad (4,68)$$

$$\omega = 2\pi f, \qquad (4,69)$$

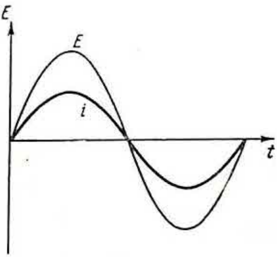


Fig. 61. Graph of alternating e.m.f. and current (sine law, $\varphi = 0$).

where I_m and U_m are the maximum values (amplitudes) of the current and the voltage, ω is the angular (cyclic) frequency of the current, t—the time, φ—the phase shift between the current and the voltage (see p. 80), f—the frequency of the current.

The *effective value* of an alternating current (I) is defined as the direct current which would develop the same power in an active resistance as the given alternating current.

In most cases (but not always!) ammeters and voltmeters show the effective values of the current or voltage.

For sinusoidal currents

$$I = \frac{I_m}{\sqrt{2}}, \qquad (4,70)$$

$$U = \frac{U_m}{\sqrt{2}}. \qquad (4,71)$$

An inductor L (a device possessing inductance) in an alternating-current circuit acts like a resistance R_L in the circuit, i. e., it reduces the current.

The quantity R_L which describes the behavior of an inductor is called the *inductive reactance*:

$$R_L = \omega L, \qquad (4,72)$$

and is due to the appearance of an e.m.f. of self-induction in the coil.

An alternating current in an inductor lags behind the voltage by 90°.

A capacitor in an alternating-current circuit conducts current (as distinct from direct current!). The quantity which describes the behavior of a capacitor in an alternating-current circuit is called the *capacitive reactance*:

$$R_C = \frac{1}{\omega C}. \qquad (4,73)$$

The current in a capacitor leads the voltage by 90°.

In a circuit containing resistance, inductive reactance and capacitive reactance connected in series the quantity

$$Z=\sqrt{R^2+\left(\omega L-\frac{1}{\omega C}\right)^2}, \tag{4,74}$$

called the *impedance*, is analogous to the resistance of a direct-current circuit.

For $R_L=R_C$ the impedance is a minimum (see formula (4,74)), and the current has its maximum value. This phenomenon is called *series resonance*.

The phase difference between the current and the voltage is determined from the relations:

$$\left.\begin{aligned}\tan\varphi&=\frac{\omega L-\frac{1}{\omega C}}{R},\\ \cos\varphi&=\frac{R}{Z}.\end{aligned}\right\} \tag{4,75}$$

The power developed by an alternating current in the circuit is

$$P=UI\cos\varphi. \tag{4,76}$$

The factor cos φ is called the *power factor*.

When an alternating current passes through a conductor it generates induced currents; as a result the current density will be greater at the surface of the conductor than in the middle. The difference will be the greater, the greater the frequency (at high frequencies the current in the middle of the conductor may be practically zero). The active resistance of a conductor will therefore be greater to alternating current, than to direct current. This phenomenon is called the *surface effect* (or *skin effect*).

TABLES AND GRAPHS

Resistance to Direct and Alternating Current

The change in resistance depends on a parameter ξ:

$$\xi=0.14\,d\sqrt{\frac{\mu f}{\varrho}},$$

where d—is the diameter of the wire (cm), f—the frequency (c/sec), ϱ—the resistivity (ohm cm), μ—the permeability, R_{ac}—the resistance of the wire to alternating current, R_{dc}—the resistance of the same wire to direct current.

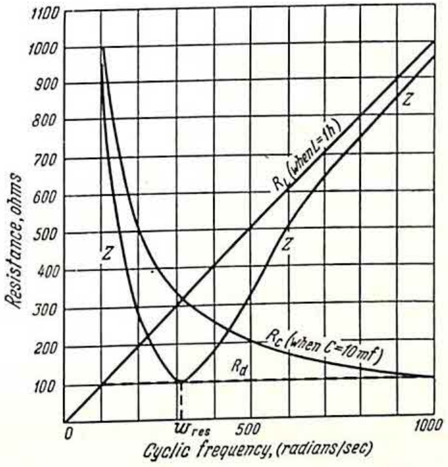


Fig. 62. Graph of R_{ac}/R_{dc} versus ξ.

Variation of Inductive Reactance, Capacitive Reactance and Impedance with Frequency

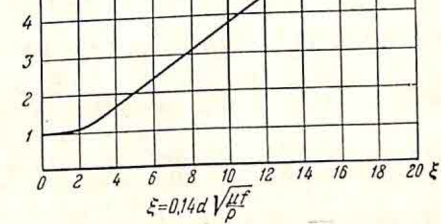


Fig. 63. Graphs of R_L, R_C, and Z versus ω for $L=1$ henry, $C=10$ μfd, $R_a=100$ ohms (it is assumed that R_a is independent of the frequency).

Table 97

Depth of Penetration (σ) of High Frequency Currents (for a Straight Copper Wire with Circular Cross-Section)

Frequency	10 kc/sec	100kc/sec	1 Mc/sec	10 Mc/sec	100 Mc/sec
Depth of penetration, mm	0.65	0.21	0.065	0.021	0.006

Notes. 1. Calculations can be made for other frequencies and other materials by means of the formula

$$\sigma = 50.33 \sqrt{\frac{\varrho}{\mu f}},$$

where ϱ is the resistivity (ohm mm²/m), μ—the permeability of the material, f—the frequency (c/sec).

2. The depth of penetration is the distance from the surface of the wire at which the current density is e times less than at the surface, where e is the base of natural logarithms ($e \approx 2.72$).

E. ELECTRIC OSCILLATIONS AND ELECTROMAGNETIC WAVES

FUNDAMENTAL CONCEPTS AND LAWS

Oscillatory variations of the charge, current or voltage in an electric circuit are called *electric oscillations*. An alternating electric current is an example of electric oscillations. High-frequency electric oscillations are generated as a rule by means of an oscillating circuit. An *oscillating circuit* is a closed circuit containing inductance L and capacitance C.

The *period of natural oscillations* of a circuit is

$$T_0 = 2\pi \sqrt{LC}. \qquad (4,77)$$

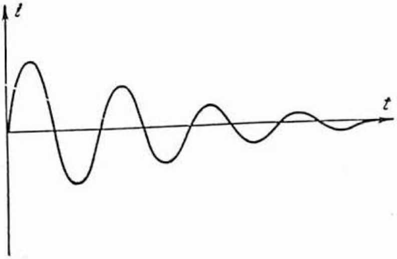


Fig. 64. Graph of current in circuit with damped oscillations.

This relation is called *Thomson's formula*; it is valid in the absence of energy losses. In the case of energy losses in the circuit (when an ohmic resistance is present) the natural oscillations of the circuit are damped:

$$T = \frac{2\pi}{\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}}. \quad (4.78)$$

The term $\frac{R}{2L}$ is usually very small. Fig. 64 represents a graph of damped oscillations in a circuit.

When an alternating e.m.f. is applied to the circuit, forced oscillations arise in it. The amplitude of the forced oscillations will be greatest when the natural frequency of the circuit coincides with the frequency of the sinusoidal e.m.f. (Fig. 65). This phenomenon, which finds wide application in radio engineering, is called *electric resonance*.

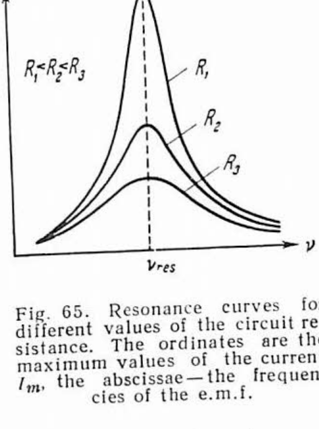
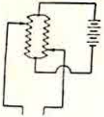


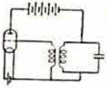
Fig. 65. Resonance curves for different values of the circuit resistance. The ordinates are the maximum values of the current I_m, the abscissae—the frequencies of the e.m.f.

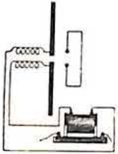
The amplitudes of the charge and the voltage in forced oscillations are greatest when the frequency of the imposed e.m.f. differs slightly from the natural frequency of the circuit.

(cont.)

		10^8 km		10^6 km			10^3 km			1 km				1 m	1 dm
1		10^{13} cm		10^{11}			10^8			10^5				10^2	
2		$3 \cdot 10^{-3}$ c/s					$3 \cdot 10^2$			$3 \cdot 10^5$				$3 \cdot 10^8$	
3	Low frequency waves								Radio waves						
4	Very low frequencies		Low frequencies		Commercial frequencies	Audio frequencies			Long waves	Medium waves	Intermediate waves	Short waves	Meter waves	Decimeter waves	
5	Electrical oscillations of dipoles														
6															
7	Cathode oscillator														
8	Asynchronous generator with rheostat				A.c. generator			Thomson circuit						Hertzian oscillator	







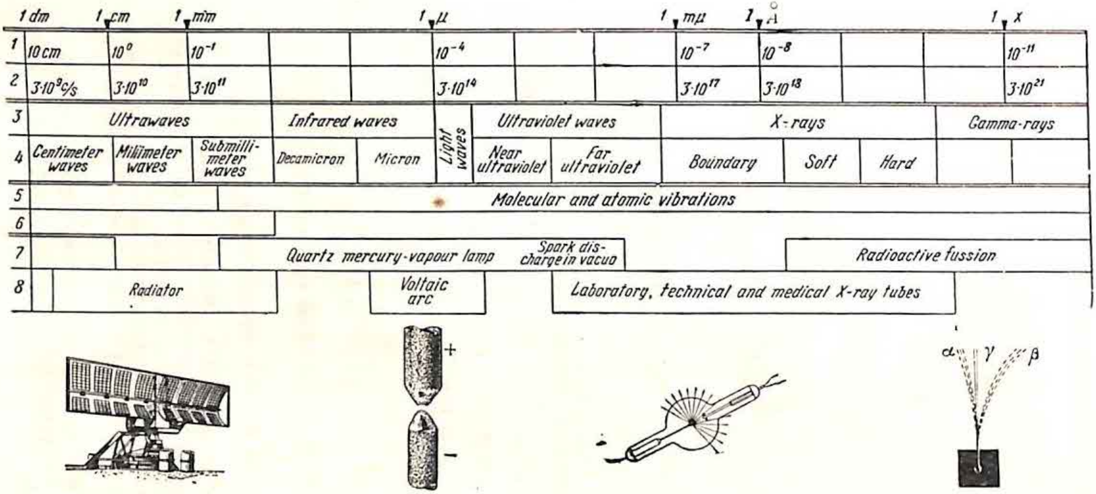


Fig. 67. Electromagnetic spectrum

Electromagnetic waves represent a process of simultaneous propagation of variable electric and magnetic fields. The vectors of the electric and magnetic field intensities (E and H) in an electromagnetic wave are perpendicular to each other and to the direction of propagation of the waves (Fig. 66). This is true for the propagation of electromagnetic waves in vacuum.

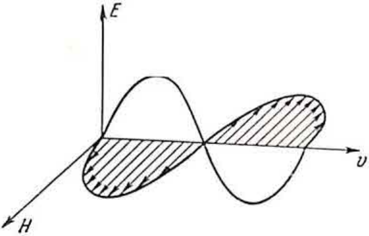


Fig. 66. Vectors E, H, and v in electromagnetic wave.

The velocity of electromagnetic waves in vacuum is independent of the wavelength and equals

$$c_0 = (2.99776 \pm 0.00004) \times 10^{10} \text{ cm/sec.}$$

The velocity of electromagnetic waves in different media is less than in vacuum:

$$c = \frac{c_0}{n}, \qquad (4,79)$$

where n is the index of refraction (see p. 160).

The Electromagnetic Spectrum

The wavelengths are plotted logarithmically.

The first horizontal row gives the wavelengths (upper values in different units of length, lower values in cm).

The second row gives the frequencies in cycles/sec, the third and fourth rows—the names of the wavelength and frequency ranges.

Rows 5 and 6 show the types of electromagnetic radiators, rows 7 and 8—the principal methods of generating electromagnetic oscillations.

Low-frequency and radio waves have the lowest frequencies; such waves are generated by various artificial oscillators.

Infrared radiation is emitted mainly by oscillating parts of molecules or groups of atoms.

Light waves are emitted by atoms and molecules when electrons in the outer shell pass from one stable orbit to another (see p. 190).

Ultraviolet rays have the same origin as light waves.

X-rays are emitted when electrons in the inner shells of atoms pass from one orbit to another.

Gamma-rays are emitted in the radioactive decay of atomic nuclei.

Further information on the properties of various types of waves will be found in Chapter V: Optics.

CHAPTER V

OPTICS

FUNDAMENTAL CONCEPTS AND LAWS

Light is electromagnetic radiation of wavelength considerably shorter than that of radio waves (see the electromagnetic spectrum). Such radiation is emitted by atoms when their electrons jump from one orbit to another (see p. 190).

1. Photometry

The energy radiated by a body per second is called the *intensity of radiation*. The energy transmitted by a light wave per second to a surface is called the *flux of radiation* through the surface Φ. The flux of radiation as estimated visually is called the *luminous flux*. Since the sensitivity of the eye varies for different wavelengths, the ratio of the flux of radiation to the luminous flux will also depend on the wavelength. As a rule, in daytime vision the eye is most sensitive to radiation of 5,550 Å. The ratio of the intensity of radiation of 5,550 Å to the intensity of radiation of wavelength λ which causes the same visual sensation is called the *relative brightness sensitivity* of the eye (K_λ). The curve of K_λ versus λ is called the *curve of relative brightness sensitivity*.

The *luminous intensity* (I) is defined as the luminous flux emitted by a point source of light into unit solid angle.

$$I = \frac{\Phi}{\Omega}, \qquad (5,1)$$

where Φ is the luminous flux, and Ω—the solid angle.

The unit of luminous intensity is called the *candela*.*

---

* The present standard of luminous intensity is constructed in the form of a black body radiator (Fig. 68; see also p. 170) kept at the temperature of molten platinum, at 2,042.6° K.

The unit of luminous flux is the *lumen*. One lumen is equal to the luminous flux contained in a solid angle of one *steradian* when the luminous intensity is one *candela*.

Prior to the introduction of the new standard *candela*, the *international candle* in the form of electric bulbs of special design was used as the standard of luminous intensity.

1 international candle = 1.005 candelas.

The *illuminance* (E) is the luminous flux incident on unit area of a surface:

$$E=\frac{\Phi}{S}, \qquad (5,2)$$

where S is the surface area receiving the luminous flux.

The units of illuminance are the *lux* and the *phot*:

$$1\ \text{lux}=1\ \text{lumen/m}^2,$$
$$1\ \text{phot}=1\ \text{lumen/cm}^2.$$

The brightness of an extended light source (or surface seen by reflected light) is referred to technically as its *luminance* (B):

$$B=\frac{I}{S}, \qquad (5,3)$$

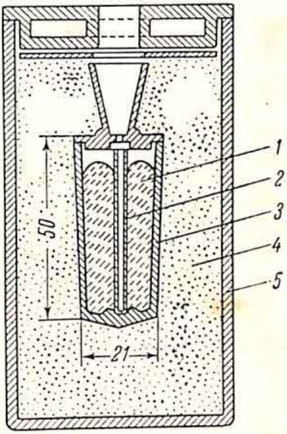


Fig. 68. USSR State standard light source: 1—platinum, 2—fused thorium oxide tube, 3—fused thorium oxide cup, 4—thorium oxide powder, 5—silica container.

where S is the visible area of the surface (the area of the projection of the surface on to a plane perpendicular to the line of vision), and I is the luminous intensity.

Luminance is expressed in units of luminous intensity per unit area, as candelas/m^2.

An old unit of luminance is the *stilb*.

A stilb is equal to the luminance of a source which radiates a luminous intensity of 1 candela per cm^2 of luminous surface.

$$1\ \text{stilb}=10^4\ \text{candelas/m}^2.$$

Photometry deals with luminous intensity, luminance and illuminance, as determined by visual perception and from measurements of the luminous flux.

2. Principal Laws of Geometrical Optics

Geometrical optics deals with those phenomena which can be explained on the assumption that light travels through a homogeneous medium in a straight line.

The *angle of incidence* is the angle between the incident ray and the normal to the interface between two media at the point of incidence. The *angle of reflection* is the angle between this normal and the reflected ray. The *angle of refraction* is the angle between the normal and the refracted ray.

1. When a ray is incident on the interface between two media the angle of incidence is equal to the angle of reflection. The incident ray, the normal, and the reflected ray all lie in the same plane.

The magnitude of reflection is characterised by the *reflection coefficient* ρ, which is equal to the ratio of the energy flux in the reflected wave to that in the incident wave.

(The reflection coefficient is frequently expressed in per cent.)

2. The ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant (for a given wavelength). The incident ray, the normal, and the refracted ray are in the same plane.

$$\frac{\sin i}{\sin i'} = n. \tag{5,4}$$

The quantity n is called the *relative index of refraction* of the second medium with respect to the first medium, and is equal to the ratio of the velocities of light in the two media: $n = \frac{c_1}{c_2}$.

The index of refraction with respect to vacuum is called the *absolute index of refraction* of the medium. The index of refraction n depends on the wavelength.

A ray passing from a medium with a greater index of refraction to a medium with a smaller index of refraction can undergo *total reflection*. The least angle of incidence i_{cr} at which all the energy of the light is reflected from the interface is called the *critical angle*. The magnitude of the critical angle i_{cr} is determined from the formula

$$\sin i_{\mathrm{cr}} = \frac{1}{n},$$

where n is the relative index of refraction of the medium in which total reflection takes place.

Rough surfaces reflect light rays in all directions (*diffuse reflection*), as a result of which they are visible to the eye.

When light passes through thin metal plates its intensity is reduced. The change in the luminous intensity (for normal incidence on the plate) is given by the relation

$$I_x = I_0 e^{-4\pi n \frac{x}{\lambda} k},$$

where I_0 is the incident light intensity, I_x—the intensity of the light after passage through a plate of thickness x, λ—the wavelength, e—the base of natural logarithms, n and k—*optical constants* of the metal which are determined from the relations

$$n^2 k = \frac{\sigma}{\nu}, \quad n^2 (1 - k^2) = \varepsilon.$$

Here σ is the conductivity of the metal, ν—the frequency of the light wave, and ε—the dielectric constant.

3. Optical Instruments

The formula of a thin lens (Fig. 69) is

$$-\frac{1}{a} + \frac{1}{a'} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right) = \frac{1}{f}, \qquad (5,5)$$

where a is the distance from the lens to the object, a'—the distance from the lens to the image, f—the *focal length* of the lens, r_1 and r_2—the radii of curvature of the spherical surfaces of the lens, n—the relative refractive index of the material of the lens.

In formula (5,5) the quantities a, a', r_1, and r_2 are considered positive when their directions, as measured from the lens, coincide with the direction of the light rays; otherwise they are considered negative.

The magnification of a magnifying glass is

$$M = \frac{250}{f}, \qquad (5,6)$$

where f is the focal length in millimeters.

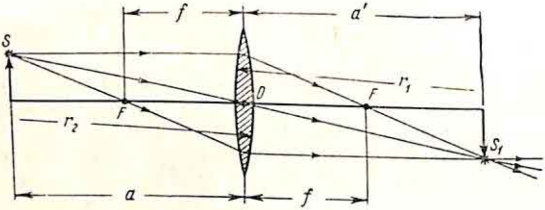


Fig. 69 Path of rays in thin converging lens.

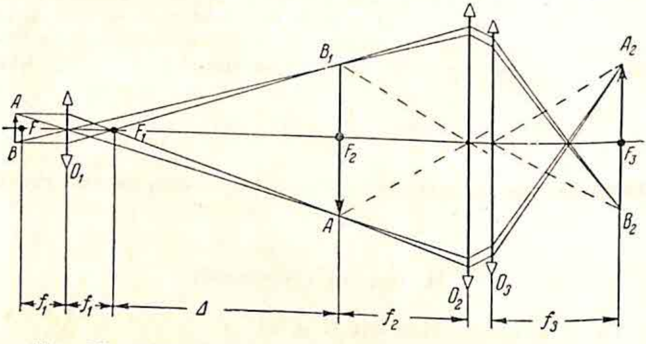


Fig. 70. Path of rays in microscope. O_1 and O_2 — lenses equivalent to microscope objective and eyepiece, O_3 — lens equivalent to optical system of observer's eye, A_2B_2 — image of AB on retina of eye.

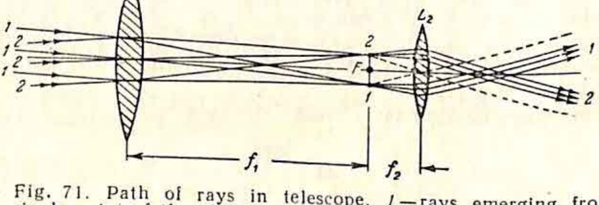


Fig. 71. Path of rays in telescope. 1 — rays emerging from a single point of the object, 2 — rays emerging from another point of the object.

The overall magnification of a microscope is

$$M=\frac{\Delta}{f_1}\times\frac{250}{f_2}, \quad (5,7)$$

where f_1 and f_2 are the focal lengths of the objective and the eyepiece in millimeters, Δ is the distance from the upper focus of the objective to the lower focus of the eyepiece in millimeters (Fig. 70).

The magnification of a telescope is

$$M=\frac{f_1}{f_2}, \quad (5,8)$$

where f_1 and f_2 are the focal lengths of the objective and the eyepiece (Fig. 71).

The reciprocal of the focal length is called the *power* of the lens: $D=\frac{1}{f}$. The unit of power of a lens is the *diopter* (D), equal to the power of a lens with a focal length of 1 m.

4. Wave Properties of Light

Interference. When two waves travel simultaneously through a medium there will be a resultant vibration of the particles of the medium at each point (in the case of mechanical waves), or a resultant oscillation of the electric and magnetic field intensities (in the case of electromagnetic waves). The resultant oscillations will be determined by the amplitude and the phase of each of the waves.

The superposition in space of two (or more) waves of the same period leading to a reinforcement of the resultant amplitude at some points and to a diminution of the amplitude at others is called *interference*.

Interference of waves of any kind (including light waves) takes place only if the superposed waves have the same period and a constant phase difference at each point. Sources which generate such waves are called *coherent*. For polarised waves (see p. 167) to display interference it is necessary in addition, that their planes of polarisation coincide.

Coherent sources of light can only be obtained artificially.

In a homogeneous medium every colour corresponds to a definite frequency of the wave. When a wave passes into another medium, the wavelength changes, but the frequency remains the same.

Daylight consists of electromagnetic radiation of various wavelengths (corresponding to colours from red to violet).

The colours of thin films are due to the interference of waves reflected from the upper and lower surfaces of the film (when observed in reflected light). When observed in transmitted light interference takes place between the transmitted waves and the waves reflected from the upper and lower surfaces of the film.

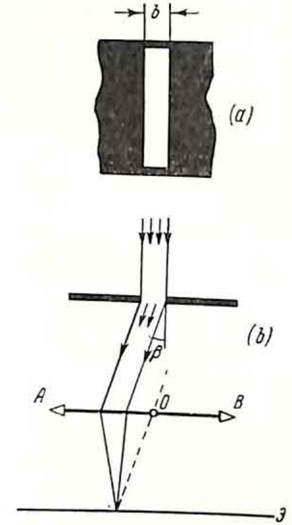


Fig. 72. Diffraction of parallel rays by a single slit. *a*) Schematic diagram of slit, *b*) a possible direction of the diffracted rays, *AB*—lens, *O*—optical centre of lens, *S*—screen in focal plane of lens.

Diffraction. The deflection of light from a rectilinear path otherwise than by reflection or refraction is called *diffraction*. Fig. 72 depicts schematically a long narrow slit, by means of which it is possible to observe the phenomenon of diffraction. Light falls perpendicularly on the surface containing the slit. Upon passing through the slit the light rays are deflected from a straight path, and as a result of the subsequent superposition (interference) of the light waves one will observe light and dark fringes on the screen.

The positions of the dark fringes are determined by the condition

$$b \sin \beta = n\lambda, \qquad (5,9)$$

where β is the angle between the normal and the given direction, n—an integer, and b—the width of the slit.

A series of narrow parallel equi-distant slits of equal width is called a *diffraction grating*. The width of a slit plus the distance between two adjacent slits is called the *grating interval*.

Fig. 73 gives a schematic depiction of a diffraction grating. The positions of the fringes of maximum intensity on the screen are determined from the condition (for normal incidence of light on the grating):

$$d \sin \alpha = n\lambda, \tag{5,10}$$

where d is the grating interval.

Due to the diffraction of light waves there is a limit to the ability of optical instruments to show increasingly greater detail on the surface of an object at higher magnifications.

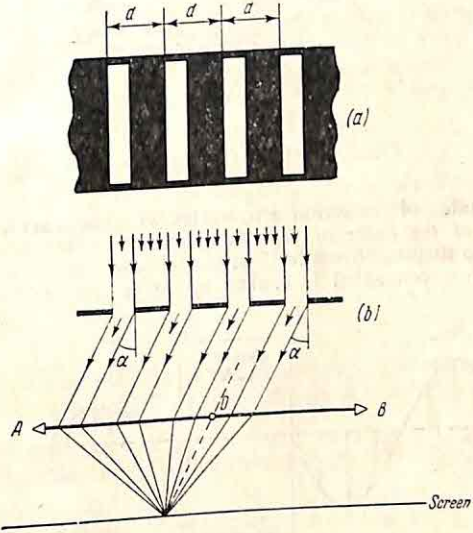


Fig. 73. Diffraction of parallel rays by a diffraction grating. *a*) Schematic diagram of part of grating, *b*) a possible direction of the diffracted rays, *AB*—lens, *O*—optical center of lens, *S*—screen in focal plane of lens.

The smallest distance between two points at which their images do not overlap is called the *least separation for resolution* of an optical instrument (δ).

For a microscope the least separation for resolution is:

$$\delta = \frac{0.61\lambda}{\sin u}, \tag{5,11}$$

where u is the *aperture* angle (half the angle subtended by the extreme rays from a point on the object which enter the objective and reach the observer's eye).

Dispersion of light. The velocity of light in a given medium depends on the wavelength. This phenomenon is called *dispersion of light velocity*.

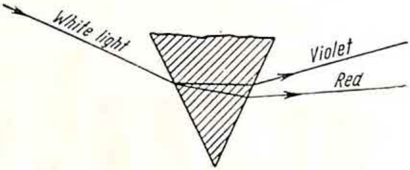


Fig. 74. Path of rays in glass prism.

The index of refraction also varies with the wavelength (*dispersion of the index of refraction*).

Due to dispersion white light (which consists of radiation of different wavelengths) is broken up by a glass prism into its components. Rays of shorter wavelength are bent towards the base of the prism more strongly than waves of greater wavelength (Fig. 74).

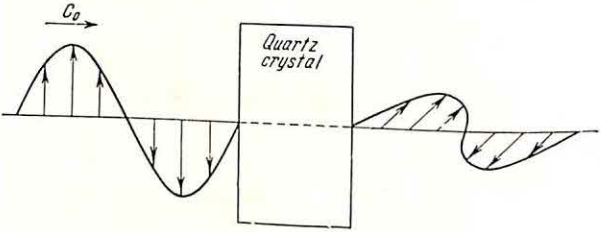


Fig. 75. Rotation of plane of polarisation of polarised ray in quartz plate.

Polarisation of light. In the light waves emitted by different sources the vectors E (and, hence, H) are oriented randomly. Such light is called *natural* light.

It is possible (for example, by passing natural light through a plate of tourmaline) to obtain waves in which the H vectors will have a single direction at all points in space. Such waves are called *linearly polarised* (or plane polarised).

In linearly polarised light each of the vectors E and H lies in a given plane. The plane of the vector of magnetic field intensity H is called the *plane of polarisation*. Some substances (for example, quartz, aqueous solutions of sugar) have the ability to turn the plane of polarisation of linearly polarised light passing through them. This phenomenon is called *rotation of the plane of polarisation* (Fig. 75).

Light can be partially polarised by reflection from a dielectric. At a certain angle of incidence the reflected light is completely polarised. This angle is called the *polarising angle*. It can be determined from a relation called Brewster's law:

$$\tan i_{\mathrm{p}} = n, \qquad (5,12)$$

where n is the index of refraction.

Pressure of light. When electromagnetic waves strike the surface of a body they exert mechanical pressure upon it (called the *radiation pressure*).

The magnitude of the radiation pressure is given by

$$p = \frac{W}{c}(1+\rho), \qquad (5,13)$$

where W is the quantity of radiation energy incident normally on 1 cm^2 of surface per sec, c—the velocity of light, ρ—the reflection coefficient.

The pressure exerted by the sun's rays on a bright day is equal approximately to 0.4 dyne/m^2 (4×10^{-5} dyne/cm^2).

5. Quantum Properties of Light

The energy of any form of electromagnetic radiation, including light, always exists in the form of discrete portions. These portions of energy, which possess the properties of material corpuscles, are called *radiation quanta* or *photons*. The energy of a photon depends on the frequency of the radiation ν.

The energy of a photon $\varepsilon = h\nu$, where $h = 6.623\times10^{-27}$ erg sec. The constant h is called *Planck's constant*.

According to the fundamental principles of modern physics (theory of relativity), whenever the energy of a system changes by an amount ε there is an equivalent change in the mass of the system equal to $\frac{\varepsilon}{c^2}$ (c is the velocity of light). Hence, for every photon emitted by a body its mass decreases by an amount $\Delta m=\frac{h\nu}{c^2}$.

Those properties of light which are due to the discrete nature of radiation are called *quantum* (or *corpuscular*) properties.

Light, like all other forms of electromagnetic radiation, possesses both wave and corpuscular properties.

The *photoelectric effect* is one of the manifestations of the corpuscular nature of light. The emission of electrons from the surface of an illuminated body is called the *external photoelectric effect*.

Laws of the external photoelectric effect. 1. The saturation current is directly proportional to the light flux, the spectral composition of the light remaining constant.

2. The maximum velocity of the emitted electrons is independent of the light intensity, and is determined by the frequency of the incident light. It may be found from the equation

$$h\nu=\varphi+\frac{mv^2}{2}, \qquad (5,14)$$

where $h\nu$ is the energy of a photon, φ—the work function (see p. 116), m—the mass of the electron, and v—its velocity. Equation (5,14) is called *Einstein's equation*.

3. For every substance there exists a frequency below which the photoelectric effect is not observed. This critical frequency is called the *photoelectric threshold* (ν_{cr}). It is determined from the relation

$$h\nu_{cr}=\varphi. \qquad (5,15)$$

When semiconductors and dielectrics are illuminated, some of their atoms may lose electrons, which, however, (in contradistinction to the external photoelectric effect) do not escape through the surface of the body, but remain inside the body. This phenomenon is called the *internal photoelectric effect*. As a result of the internal photoelectric effect the resistance of semiconductors and dielectrics decreases upon illumination.

When the interface between a metal and a semiconductor is illuminated, an electromotive force arises. This phenomenon is called the *barrier-layer effect*.

Photoelectric cells, photoconductive cells, barrier-layer cells and solar batteries are based on the photoelectric phenomena.

The *photoelectric cell* is based on the external photoelectric effect. It consists of a sealed glass bulb containing a light-sensitive cathode and an anode. The cathode is a thin film deposited

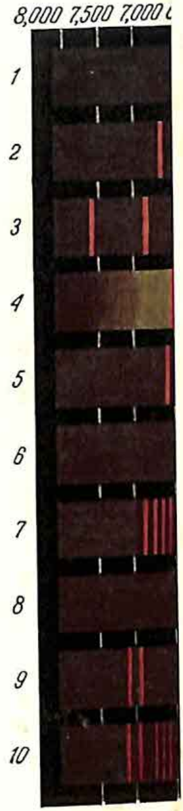


Fig. 77. Line spe

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on the inner surface of the bulb; the anode is a ring (or disc) placed in the centre of the bulb. The two electrodes are connected through an external battery.

When the cathode is illuminated a galvanometer in the circuit registers a photoelectric current:

$$i_{\Phi}=\gamma\Phi+i_0,$$

where Φ is the flux of radiant energy, γ—the *integral sensitivity* of the photoelectric cell, i_0—the *dark current*, i. e., the current in the photoelectric cell in complete darkness.

Photoelectric cells which are based on the internal photoelectric effect are called *photoconductive cells*. The sensitivity of photoconductive cells is characterised by the *specific sensitivity* (K). This quantity is equal to the ratio of the integral sensitivity to the applied potential difference U, i. e.,

$$K\cong\frac{i_{\Phi}}{U\Phi}\,.$$

Photoconductive cells are also characterised by the magnitude of the ratio $\frac{R_d}{R_{\Phi}}$, where R_d is the resistance in the dark and R_{Φ} is the resistance upon illumination.

6. Thermal Radiation

Heated bodies emit invisible waves (so-called *ultraviolet* and *infrared* rays) in addition to visible light. The radiation of heated bodies is called *thermal* (or *heat*) *radiation*.

A body which completely absorbs all the radiation incident on it is called a *black body* (or *perfect absorber*). A hollow box with a small hole in it is a black body.

The rate at which a body radiates energy of a given wavelength from unit surface of the body is called the *emissive power* or *emissivity* at the given temperature (E_{λ}).

The fraction of the incident radiation of a given wavelength λ which is absorbed by a body is called the *absorptive power* or *absorptivity* (A_{λ}). The emissivity at a given temperature is proportional to the absorptivity at the same temperature (Kirchhoff's law):

$$\frac{E_{\lambda}}{A_{\lambda}}=\varepsilon_{\lambda}, \qquad (5,16)$$

where ε_λ at a given temperature is a constant for all bodies.

For a black body $A_\lambda = 1$ and, hence $E_\lambda = \varepsilon_\lambda$ for all wavelengths.

The rate of radiation of energy of all wavelengths from a black body (ε) is proportional to the fourth power of the absolute temperature (Stefan-Boltzmann's law):

$$\varepsilon = \sigma T^4, \tag{5.17}$$

where the coefficient of proportionality $\sigma = 5.67 \times 10^{-12}$ watt/cm^2 degree^4.

7. Types of Spectra

The dependence of the intensity of radiation of a body on the wavelength (or frequency) is called the *spectrum of radiation.* This dependence is usually depicted in graph form. For example,

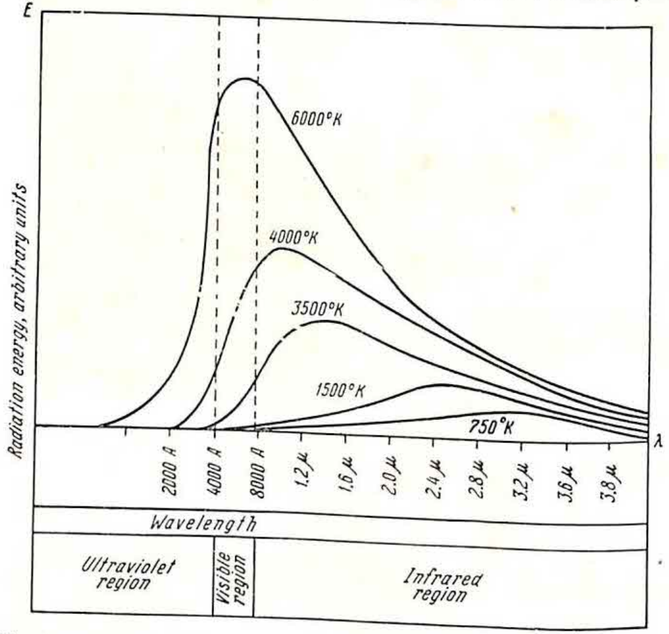


Fig. 76. Energy distribution in spectrum of incandescent carbon at different temperatures.

Fig. 76 gives the spectrum of thermal radiation of carbon for different temperatures. This spectrum closely resembles that of a black body.

It is evident from the figure that at any given temperature there is a certain wavelength ($\lambda_{\max}$) for which the energy of radiation is a maximum. For a black body the wavelength corresponding to the maximum energy of radiation is inversely proportional to the absolute temperature T (Wien's law of displacement):

$$\lambda_{\max} T = C, \tag{5,18}$$

where C is a constant, equal to 0.2898 cm degree^{-1}.

The coloured band obtained when light is broken up by a prism (or other device) is sometimes called a *spectrum* (*in the narrow sense of the word*).

Heated solids emit a *continuous spectrum* in which all the spectral colours are present, one colour merging gradually into the next.

In *line spectra* the intensity of radiation is high only within very narrow regions contiguous to definite wavelengths, while at other wavelengths it is practically zero.

Line spectra are emitted by gases of low density. If such a spectrum is dispersed by a prism (or other instrument) narrow lines of different colours are obtained (Fig. 77). The number of these lines and their wavelengths are characteristic for each element. An analysis of the lines in the spectrum thus allows us to identify the elements which are present in the given substance.

The spectra of heated gases and solids are called *emission spectra.*

If the radiation emitted by a heated solid is passed through a vapour, then in the continuous spectrum of the body dark lines appear, at wavelengths corresponding to the lines of the emission spectrum of the given vapour. Such a spectrum is called an *absorption spectrum.*

Gases absorb radiation of the same wavelength as they themselves emit (law of Kirchhoff and Bunsen).

The so-called *Fraunhofer lines* in the solar spectrum (see Fig. 78) are absorption lines due to the absorption of definite wavelengths of the continuous solar spectrum by vapours present in the atmosphere.

TABLES AND GRAPHS

Table 98

Relative Brightness Sensitivity (K_λ) for Daytime Vision

(see Fig. 79)

Wavelength, Å	K_λ	Wavelength, Å	K_λ	Wavelength, Å	K_λ
4,000	0.0004	5,200	0.710	6,400	0.175
4,200	0.0040	5,400	0.954	6,600	0.061
4,400	0.023	5,600	0.995	6,800	0.017
4,600	0.060	5,800	0.870	7,000	0.0041
4,800	0.139	6,000	0.631	7,200	0.00105
5,000	0.323	6,200	0.381	7,400	0.00025
				7,600	0.00006

Note. The values of the relative brightness sensitivity are different for different people. They do not vary, however, too widely for people with normal vision. The table gives average values of K_λ.

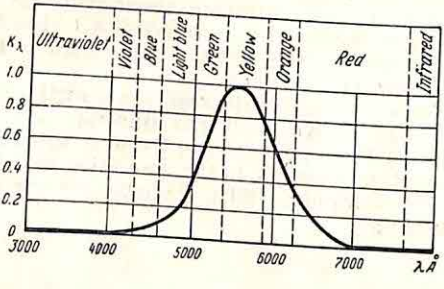


Fig. 79. Curve of relative brightness sensitivity for daytime vision.

Table 99

Luminance of Illuminated Surfaces

Illuminated surface	Luminance, candelas/m²
Cinema screen	5-2
Sheet of white paper (under illuminance 30-50 lux)	10-15
Snow in direct sunlight	3×10^4
Moon's surface	2.5×10^3

Table 100

Luminance of Various Light Sources

Source	Luminance, candelas/m²
Sun	15×10^8
Capillary of superhigh pressure mercury arc	12×10^8-15×10^8
Carbon arc crater	15×10^7
Metal filament of incandescent lamp	$1\ 5\times10^6$-2×10^6
Kerosene lamp flame	1.5×10^4
Stearine candle flame	5×10^3
Moonless night sky	10
Spark discharge in xenon	1.1×10^{11}
" " " argon	1.5×10^{11}
" " " air (nitrogen)	2.1×10^{11}
" " " helium	1.5×10^{12}

Table 101

Illuminance in Some Typical Cases

Illumination	Illuminance, lux
Sun's rays at noon (middle latitudes)	100,000
During film shooting in studio	10,000
Open area on a cloudy day	1,000
Light room (near window)	100
Work table for delicate operations	100-200
Illumination necessary for reading	30-50
Cinema screen	20-80
Illumination from full moon	0.2
Illumination from moonless night sky	0.0003

Table 102

Reflection Coefficient (ρ) of Glass and Water for Different Angles of Incidence (in %)

Angle of incidence, degrees / Substance	0	20	30	40	50	60	70	80	89	90
Glass	4 7	4.7	2.2	2.5	3.4	6.0	13.5	34.5	90.0	100
Water	2	2.1	4.9	5.3	6.6	9.8	18	39	91	100

Note. For glass covered with a film of silica of index of refraction 1.5, $\varrho \cong 2.5$ at normal incidence. For glass with a film of silica of index of refraction 1.9, $\varrho \cong 0.8$ at normal incidence.

Table 103

Reflection of Light Passing from Glass into Air

Angle of incidence	0°	10°	20°	30°	35°	39°	39°30′	40°	60°
Angle of refraction	0°	15°40′	32°	51°	63°	79°	82°	90°	—
Fraction of reflected energy in %	4.7	4.7	5.0	6.8	12	36	47	100	100

Table 104

Wavelengths of Visible Region of Spectrum

Colour	Boundaries, Å	Colour	Boundaries, Å
Violet	3,800-4,500	Yellowish-green	5,500-5,750
Dark blue	4,500-4,800	Yellow	5,750-5,850
Light blue	4,800-5,100	Orange	5,850-6,200
Green	5,100-5,500	Red	6,200-7,600

Table 105

Wavelengths of Ultraviolet Region of Spectrum

Name of range	Boundaries, Å	Effect of Radiation
Long wavelength ultraviolet	3,150-3,800	Suntan
Middle wavelength ultraviolet	2,800-3,150	Erythemogenic
Short wavelength ultraviolet	2,000-2,800	Bactericidal
Vacuum ultraviolet	<2,000	Ozonising

Table 106

Reflection of Light by Metals

The figures in the table indicate the fraction of perpendicularly incident light reflected from the surface (in %)

Spectral region	Wave-length, Å	Alum-inium	Copper	Iron	Silver	Nickel	Chro-mium	Zinc	Silicon
Ultraviolet	1,880	25	23	—	22	35	—	17	64
	2,000	31	31	—	25	44	—	22	73
	2,510	53	26	—	33	38	—	39	75
	3,050	64	29	—	47	—	—	48	73
	3,570	70	32	—	67	49	—	51	60
Visible	5,000	—	44	55	90	61	55	55	34
	6,000	—	72	58	93	65	—	58	32
	7,000	—	83	60	94	69	56	61	—
Infrared	8,000	—	89	62	95	70	—	62	—
	10,000	74	90	65	96	72	57	69	—
	50,000	94	98	92	97	94	81	97	—
	100,000	97	—	—	—	—	93	—	—

Table 107

Critical Angles of Reflection

Substance	i_{cr}	Substance	i_{cr}
Water	49	Carbon disulfide	38
Glycerine	43	Glass (heavy flint)	34
Glass (light crown) . . .	40	Diamond	24

Note. The values of i_{cr} (in degrees) given in the table are for an interface with air (for the *D* line of sodium).

Table 108

Wavelengths of Principal Fraunhofer Lines

Line	Element	Wave-length, Å
A	Oxygen	7,621
a	″	7,185
B	″	6,870
C	Hydrogen	6,562.8
α	Oxygen	6,278.1
D_1	Sodium	5,895.9
D_2	″	5,890.0
D_3	Helium	5,875.6
E	Iron	5,269.6
b_1	Magnesium	5,183.6
b_2	″	5.172.7
b_3	Iron	5,169.0
b_4	Iron, magnesium	5,167.4
c	Iron	4,957.6
F	Hydrogen	4,861.3
d	Iron	4,668
e	″	4,383.6
f	Hydrogen	4,340.5
G'	Iron	4.325.8
G	Iron, calcium	4,307.9
g	Calcium	4,226.7
h	Hydrogen	4,101.7
H	Calcium	3,963.6
K	″	3,933.6

Table 109

Index of Refraction for Wavelengths Corresponding to Some of the Fraunhofer Lines

	Fraunhofer line	*A*	*B*	*D*	*F*	*H*
	Wavelength, Å	7,590	6,870	5,890	4,860	3,970
Substance	Carbon disulfide	1.610	1.617	1.629	1.654	1.702
	Ethyl alcohol	1.359	1.360	1.363	1.367	1.374
	Glass (light crown)	1.510	1.512	1.515	1.521	1.531
	Water	1.329	1.331	1.333	1.337	1.344

Table 110

Optical Constants of Metals and Semiconductors

Substance	*n*	*k*	Substance	*n*	*k*
Aluminium	1.28	3.66	Mercury	1.62	2.71
Antimony	3.4	1.63	Nickel	1.79	1.86
Bismuth	1.78	1.57	Platinum	2.07	2.12
Cesium	0.321	3.70	Potassium	0.068	21.1
Chromium	3.59	1.26	Selenium	2.85	0.221
Cobalt (6,000 Å)	2.21	1.83	Silicon	4.24	0.114
Copper	0.62	4.1	Silver	0.18	20.6
Gold	0.42	6.65	Tin	1.12	4.03
Iron	2.36	1.36	Tungsten (5,780 Å)	2.76	0.98
Lead	2.01	1.73	Zinc	2.12	2.60

Notes. 1. The values of the optical constants given in the table refer to the wavelength $\lambda=5{,}890$ Å, unless otherwise indicated.

2. The constants n and k are sometimes called the index of refraction and the index of absorption, respectively.

Table 111

Index of Refraction of Gases

Gas or vapour	Index of refraction	Gas or vapour	Index of refraction
Acetylene	1.000606	Mercury	1.000933
Air	1.000292	Methane	1.000441
Ammonia	1.000377	Nitrogen	1.000297
Benzene	1.001812	Oxygen	1.000272
Carbon dioxide	1.000450	Selenium	1.001565
Carbon tetrachloride	1.001763	Sulfur trioxide	1.000737
Chloroform	1.001455	Tellurium	1.002495
Helium	1.000035	Water vapour	1.000257
Hydrogen	1.000138	Zinc	1.002050
Hydrogen disulfide	1.000641		

Note. The values of the indices of refraction given in the table are for a wavelength corresponding to the yellow line of sodium (*D*), and are corrected for a density at 0°C and 760 mm Hg pressure by means of the formula $\frac{n-1}{\varrho}$=const (for the given gas).

Table 112

Index of Refraction of Some Solids and Liquids (at 15°C for the *D*-line of Sodium Relative to Air)

Substance	Index of refraction	Substance	Index of refraction
Solids			
Diamond	2.417	Ethyl ether	1.354
Ice	1.31	Glycerine	1.47
Mica	1.56-1.60	Methyl alcohol	1.33
Sugar	1.56	Sulfuric acid	1.43
Topaz	1.63	Turpentine	1.47
		Water (20°C)	1.333
Liquids		*Oils*	
Aniline	1.590	Cedar nut	1.516
Benzene	1.504	Cinnamon	1.601
Canada balsam	1.53	Clove	1.532
Carbon disulfide	1.632	Olive	1.46
Chloroform	1.449	Paraffin	1.44
Ethyl alcohol	1.362		

Table 113

Dependence of Index of Refraction on Wavelength

Wavelength region	Wavelength, Å	Glass (15° C)		Quartz (18° C)		Fused quartz	Water at 20° C	Sylvine (KCl) at 18° C
		light crown	heavy flint	ordinary ray	extraordinary ray			
Infrared	223,000	—	—	—	—	—	—	1.3712
	94,290	—	—	—	—	—	—	1.4387
	42,000	—	—	1.4569	—	—	—	1.4720
	21,720	1.4946	1.6153	1.5180	1.5261	—	—	1.4750
	12,560	1.5042	1.6268	1.5316	1.5402	—	1.3210	1.4778
Visible	6,708	1.5140	1.6434	1.5415	1.5505	1.4561	1.3308	1.4866
	6,438	1.5149	1.6453	1.5423	1.5514	1.4568	1.3314	1.4877
	5,893	1.5170	1.6499	1.5443	1.5534	1.4585	1.3330	1.4904
	4,864	1.5230	1.6637	1.5497	1.5590	1.4632	1.3371	1.4983
	4,047	1.5318	1.6852	1.5572	1.5667	1.4697	1.3428	1.5097
Ultraviolet	3,034	1.5552	—	1.5770	1.5872	1.4869	1.3581	1.5440
	2,144	—	—	1.6305	1.6427	1.5339	1.4032	1.6618
	1,852	—	—	1.6759	1.6901	1.5743	—	1.8270
Temperature coefficient, degree^{-1}		-1×10^{-6}	3×10^{-6}	-5×10^{-6}	-6×10^{-6}	-3×10^{-6}	-8×10^{-5}	-4×10^{-5}

Notes. 1. The refractive indices are given relative to air.

2. The temperature coefficient is the increment in the index of refraction per 1°C rise in temperature. The minus sign denotes that the refractive index decreases with rise in temperature.

3. A light ray passing through a quartz crystal is split up into two polarised rays. The table gives the indices of refraction for both rays. The maximum values are indicated for the extraordinary ray.

Table 114

Diffuse Reflection of Some Materials in White Light (in %)

Material	Reflection	Material	Reflection
Cardboard, white	60-70	Paper, blotting	70-80
" yellow	30	Paper, brown	13
Cheesecloth	16	" chocolate colour	4
Fatty clay (yellow)	24	" light blue	25
Materials coated with white paint	50	" ordinary white	60-70
Materials coated with yellow paint	40	" yellow	25
Moist earth	8	Tracing paper	22
Oil-paper (1 layer)	22	Velvet, black	0.4
" (2 layers)	35	Wood (pine)	40

Table 115

Specific Rotation of the Plane of Polarisation for Different Wavelengths at 20° C

Substance / Wavelength, Å	Quartz, degree cm³/mm g	Turpentine (pure), degree cm³/dm g	Nicotine (pure), degree cm³/dm g	Cane sugar in water, degree cm³/dm g	Tartaric acid in water, degree cm³/dm g
6,563	17.3	—29.5	—126	52.9	6.75
5,893	21.7	—37	—162	66.5	8.86
5,351	26.5	—45	—207.5	81.8	9.65
4.861	32.7	—54.5	—253.5	100.3	9.37

Notes. The rotation of the plane of polarisation is characterised by the *specific rotation* $[\alpha]_t$. For solids $[\alpha]_t=\frac{\alpha}{l\rho}$, where α is the angle of rotation of the plane of polarisation, l — the path length of the ray in the solid, ρ — the density. For liquids and solutions $[\alpha]_t=\frac{\alpha}{l\rho c}$, where α is the angle of rotation of the plane of polarisation, l — the path length of the ray in the liquid or solution, c — the concentration by weight, equal to the number of grams of solute per 100 g of solution. For pure liquids $c=1$.

2. The negative sign indicates that the rotation is clockwise if one looks at the liquid from the side of the source.

Table 116

Emission Spectra of Some Metals (in Å)

Aluminium (arc)	Copper (arc in vacuum)	Mercury (mercury lamp)	Sodium (in flame)	Cadmium (arc)	Zinc (arc in vacuum)
3,083	3,248	3,126	5,889.97 *o*	3,261	3,036
3,093	3,274	3,131	5,895.93 *o*	3,404	3,072
3,944 *v*	4,023 *v*	3,650		3,466	3,345
3,962 *v*	4,063 *v*	4,046.8 *v*		3,611	4,680 *b*
4,663 *b*	5,105.5 *g*	4,078.1 *v*		3,982 *v*	4,722 *b*
5,057 *g*	5,153.3 *g*	4,358 3 *v*		4, 413 *b*	4,811 *b*
5,696 *y*	5,218.2 *g*	4 916 4 *bg*		4,678 *b*	4,912 *b*
5,723 *y*	5,700	4 959.7 *g*		4,799.9 *b*	4,925 *gb*
	5,782 1 *y*	5.460.7 *g*		5,085.8 *g*	6,103 *o*
	5,782.2	5,769.6 *y*		5,338 *g*	6,362 *o*
		5,790.7 *y*		5.379 *g*	
		6,152 *o*		6,438.5 *r*	
		6,232.0 *o*			

Notes. 1. The wavelengths are measured in air at 15° C and 760 mm Hg pressure.

2. The colours of the visible lines are denoted by the first letter of the corresponding colour.

3. The brightest lines are underlined.

Table 117

Luminous Efficiency, Efficiency and Luminance of Some Light Sources

Type of Lamp	Luminous efficiency, lumens/watt	Efficiency, %	Temperature, °K	Luminance, candelas/m²
50-watt, carbon filament, vacuum . . .	2.5	0.4	2,095	5×10^5
50-watt, tungsten filament, vacuum . .	10	1.6	2,460	15×10^5-20×10^5
50-watt, gas-filled, tungsten filament .	10	1.6	2,685	5×10^6
500-watt, gas-filled, tungsten filament . .	17.5	2.8	2,900	10^7
2,000-watt, gas-filled, tungsten filament .	21.2	3.5	3,020	13×10^6—15×10^6
Voltaic arc	25	4	4,000	15×10^7 (crater)
Luminescent lamp . .	40	6.4	—	1.5×10^4

Note. The *luminous efficiency* is the ratio of the *total radiant* flux to the power of the current in the light source. The *efficiency* of a *light source* is the ratio of the luminous flux to the current in the source.

Table 118

Electron Work Function and Photoelectric Threshold of Various Substances

Substance	Work function, ev	Photoelectric threshold, Å
Water	6.13-6.09	2,025-2,040
Cuprous oxide	5.15	2,500
Mica	4.8	2,548
Sodium chloride	4.2	2,950
Silver bromide	3.7-5.14	3,350-2,400
Thorium on tungsten	2.62	4,730
Sodium on tungsten	2.10	5,900
Cesium on tungsten	1.36	9,090
Cesium on platinum	1.31	8,950
Barium on tungsten	1.1	11.300
Barium oxide on oxidised tungsten	1.0-1.1	12,400-11,300

Table 119

Typical Characteristics of Photoelectric Cells

Type of cell	Cathode	Filling	Integral sensitivity, μ amp/lumen	Dark current, μ amp	Operating voltage, v
ЦВ-1 ЦВ-3 ЦВ-4	Oxygen-cesium	Vacuum	20	0.1	240
ЦГ-1	ditto	Inert gases	75	0.1	240
СЦВ-3 СЦВ-51	Antimony-cesium	Vacuum	80	0.01	240
СЦВ-4	ditto	•	80	0.1	240
ЦГ-3 ЦГ-4	Oxygen-cesium	Inert gases	100	0.1	240

Table 120

Typical Characteristics of Photoconductive Cells

Type	Light-sensitive material	Sensitive area, mm²	Dark resistance R_t, ohms	Specific sensitivity, μ amp/lumen v	Maximum operating voltage, v	$\frac{R_d}{R_l}$	Mean temperature coefficient of current (from 0° C to 40° C) degree⁻¹
ФС-А4 ФС-А1	Lead sulfide	4×7	10^4-10^5	500	15	1.2	0.015
ФС-Б2	Bismuth sulfide	11×11	10^5-10^7	1,000	50	4	0.01
ФС-К2 ФС-К1	Polycrystalline cadmium sulfide	3.5×7.2 3.5×7.2	10^6 10^7	2,500 3,000	300 400	35 140	0.0012 0.014
ФСК-М1	Single crystal cadmium sulfide	28	10^{12}	—	–	—	—

Notes. 1. In view of the non-linear relation between $i_Ф$ and the flux the table gives the value of Ф for which the specific sensitivity has been determined. The table gives the mean values (for a given current) of the specific sensitivity at 1 lux.

2. The integral sensitivity of the type ФСК-М1 photoconductive cell is 2 amp/lumen at 10 lux and 60 v.

3. The current in the photoconductive cell depends on the temperature:

$$i_t \cong i_0(1+\alpha t),$$

where i_0 is the current at 0° C, i_t — the current at t° C, and α — the *mean temperature coefficient of the current.*

Table 121

Typical Characteristics of Barrier-layer Photoelectric Cells

Type	Light-sensitive material	Integral sensitivity, μ amp/lumen		Sensitive area, cm²	Internal resistance, ohms	Efficiency, %
		typical samples	best samples			
К-5	Selenium	250	500	5	10^3-5×10^4	~1
К-10	"	250	500	10	10^3-5×10^4	~1
К-20	"	250	500	20	10^3-5×10^4	~1
ФЭСС-У2	Silver sulfide	4,000	7,000-8,000	2	1.5×10^3-3×10^3	~1
ФЭСС-У3	" "	4,000	7,000-8,000	3	1×10^3-2×10^2	~1
ФЭСС-У5	" "	4,000	7,000-8,000	5	7×10^2-1.4×10^3	~1
ФЭСС-У10	" "	4,000	7,000-8,000	10	4×10^2-8×10^2	
	Thallium sulfide	5,000-6,000	10,000	2		1
	Crystalline silicon (with admixture of boron)	15,000	20,000	1-8	1-10	11-13

Notes. 1. The integral sensitivity is given for the photocurrent in the short-circuited cell.
2. The integral sensitivity for the silicon cell refers to an area of 6.5 cm².
3. A system of silicon photoelectric cells is called a *solar battery*. It is believed that the efficiency of a solar battery can be brought up to 22%.

CHAPTER VI

STRUCTURE OF THE ATOM AND ELEMENTARY PARTICLES

FUNDAMENTAL CONCEPTS AND LAWS

1. Units of Charge, Mass and Energy in Atomic Physics

The unit of charge is the *elementary charge*:

$$e_0 = 1.60 \times 10^{-19} \text{ coul.}$$

The unit of mass is equal to 1/16 of the mass of the oxygen isotope (see p. 189) with an atomic weight of 16:

$$1 \text{ atomic unit of mass} = 1.66 \times 10^{-24} \text{ g.}$$

The mass of the lightest atom—the hydrogen atom—is equal to 1.008 in this scale.

The unit of energy is the *electron-volt* (ev); it is equal to the energy acquired by an electron in falling through a potential difference of 1 volt.

$$1 \text{ ev} = 1.6 \times 10^{-19} \text{ joule} = 1.6 \times 10^{-12} \text{ erg.}$$

2. The Rutherford-Bohr Model of the Atom

The centre of the atom consists of a positively charged nucleus around which electrons revolve in definite orbits. The mass of the atom is concentrated primarily in the nucleus. The nucleus of the hydrogen atom is called a *proton*. The mass of the proton equals 1.66×10^{-24} g; that of the electron—9.11×10^{-28} g (1/1,836th part of the proton mass). The charge of the electron is equal to the elementary charge.

The charge of the nucleus is equal to the number of the element in the Mendeleyev periodic system. The number of electrons in a neutral atom is equal to the charge of the nucleus.

The motion of the electrons in the atom may be approximately described as motion in circular or elliptical orbits around the nucleus (Fig. 80). These orbits are called *stationary orbits.*

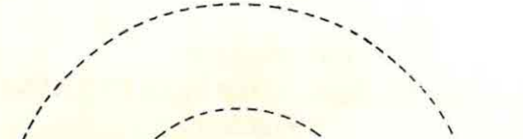


Fig. 80. Possible electronic orbits in hydrogen atom (the radii of the orbits are in the ratio of the squares of the integers $1:2^2:3^2:4^2$ etc.).

When an electron revolves about the nucleus in a stationary orbit it does not radiate. The radii of the stationary orbits are determined from the condition

$$mvr_n = \frac{h}{2\pi} n, \qquad (6,1)$$

where m is the mass of the electron, v—its linear velocity, r_n—the radius of the orbit, h—Planck's constant, $n = 1, 2, 3, \ldots$

Every stationary electron orbit (in other words, every stationary state of the atom) corresponds to a definite value of the energy (energy level).

The *energy levels* (W_n) and the radii of the circular orbits of the hydrogen atom can be computed by the formulas:

$$W_n = -\frac{2\pi^2 me^4}{n^2h^2}, \tag{6,2}$$

$$r_n = \frac{n^2h^2}{4\pi^2 me^2}. \tag{6,3}$$

An atom radiates or absorbs energy in the form of electromagnetic waves when an electron jumps from one stationary orbit to another. The magnitude of the emitted or absorbed *quantum* (portion) of energy $h\nu$ is given by the condition

$$h\nu = W_2 - W_1, \tag{6,4}$$

where W_1 and W_2 are the energy levels of the electron in the atom before and after the change of orbits.

According to contemporary views, the stationary orbits do not actually represent the trajectories of electrons in the atom. Modern physics has a somewhat different approach to the problem of the structure of the atom. However, the concept of atomic energy levels remains valid.

3. The Atomic Nucleus and the Electron Shells

The nucleus of an atom of any element is made up of protons and neutrons. The *neutron* is an electrically neutral particle whose mass is approximately equal to the mass of the proton. Nuclei of the same element may contain different numbers of neutrons, and hence may have different masses. Elements which differ only in the number of neutrons in the nucleus are called *isotopes*. The *mass number* (M) of an isotope is the whole number which is nearest to the atomic mass of the isotope. The number of neutrons in the nucleus is

$$N = M - Z,$$

where Z is the nuclear charge.

The proton and the neutron are collectively called *nucleons* (nuclear particles); inside the nucleus these particles are mutually transformed one into the other. The density of the nuclear matter is extremely high (about 100,000,000 tons/cm^3). A nucleus is denoted by the symbol of the corresponding chemical element with the atomic number as a subscript and the mass number as a superscript (for example, Al^{27} or $_{13}\text{Al}^{27}$ stands for aluminium with atomic number 13^{13} and mass number 27).

Electrons in complex atoms are grouped in *shells*. A shell includes a certain number of electronic orbits. At most two electrons can move in the same orbit.

The shell of least radius can contain at most two electrons (one orbit). This shell is called the *K-shell*. The next shell (*L-shell*) can contain up to eight electrons, the following shell (*M-shell*)—up to eighteen electrons. The third shell is subdivided into two subshells M_1 and M_2, which can contain up to eight and ten electrons, respectively (Fig. 81).

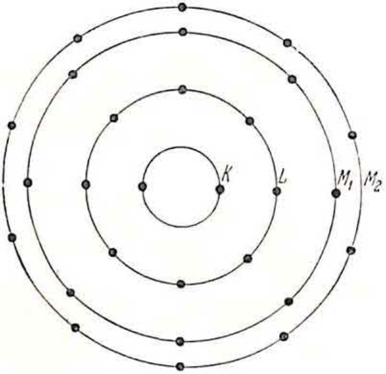


Fig. 81. Diagram of electron shells of the atom.

4. Nuclear Transformations

When a nucleus is formed by bringing together a certain number of protons and neutrons the mass of the resulting nucleus is less than the sum of the masses of the component protons and neutrons. This difference is called the *mass deficit* of the nucleus.

The energy released when neutrons and protons combine to form a nucleus is called the *binding energy of the nucleus* (E). In computations one usually deals with the quantity E/M, i. e., the binding energy per nucleon. The average value of the quantity E/M for heavy nuclei is taken equal to 8×10^6 ev.

Some heavy nuclei (uranium, thorium, radium) spontaneously disintegrate with the formation of new nuclei and the emission of α-particles, electrons and high-energy photons (γ-rays—see the electromagnetic spectrum). This property is called *radioactivity*.

The law of radioactive decay is

$$N = N_0 2^{-\frac{t}{T}}, \tag{6,5}$$

where N_0 is the original number of nuclei present at time $t=0$, N—the number of nuclei left at time t, T—the *half life*, equal to the period of time at the end of which half of the atoms of the radioactive material will have disintegrated.

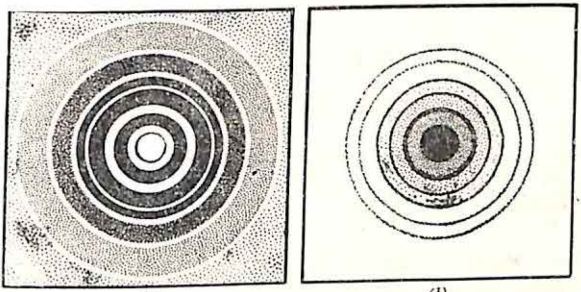

(a) (b)

Fig. 82. Diffraction of *a*) X-rays by a polycrystalline gold film, *b*) electrons by a polycrystalline gold film.

Nuclear transformations may be induced artificially by bombarding elements with protons, neutrons, helium nuclei and γ-rays. Such transformations are called *nuclear reactions*.

Nuclear reactions may lead to the formation of new radioactive isotopes, which do not occur naturally on the earth. This phenomenon is called *artificial radioactivity*.

Nuclear transformations are utilised to release nuclear energy by the fission (splitting) of heavy nuclei (for example, U^{235}) or by the synthesis (fusion) of light nuclei (for example, hydrogen nuclei). The synthesis of light nuclei requires extremely high temperatures (of the order of millions of degrees). Such reactions are called *thermonuclear*.

5. Wave Properties of Matter

Every moving particle possesses wave properties. For example, when an electron passes through a metal film we obtain a diffraction pattern similar to the diffraction patterns of X-rays and γ-rays (Fig. 82).

The wavelength of a particle is determined by the relation

$$\lambda=\frac{h}{mv}, \qquad (6,6)$$

where m is the mass of the particle, v—its velocity, and h—Planck's constant.

TABLES AND GRAPHS

Energy Levels of the Hydrogen Atom

The energy levels are calculated by means of formula (6,2) by substituting for n the successive integers 1, 2, 3, 4, etc. Utilising the energy level diagram it is easy to calculate the frequencies of the spectral lines of the hydrogen atom by means of formula (6,4).

When electrons jump to the level $n=1$ the atom emits a series of lines called the *Lyman series*; the lines of this series lie in the ultraviolet region of the spectrum. Upon transition to the level $n=2$ the lines of the *Balmer series* are emitted (four lines of this series lie in the visible part of the spectrum, the remainder—in the ultraviolet). Upon transition to the level $n=3$ the lines of the *Paschen series* are emitted (infrared region).

The numbers near the short arrows in each series indicate the longest wavelength (in Å) in the given series (1 Å$=10^{-8}$ cm).

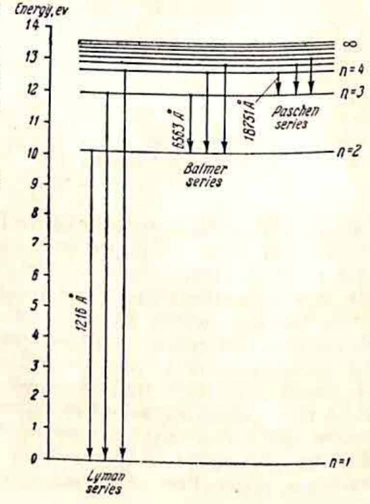


Fig. 83. Energy level diagram of hydrogen atom.

Table 122

Relative Abundance and Activity of Isotopes of Some Metals

Element	Number of protons	Number of neutrons	Relative abundance, %	Half life	Type of activity
Fe	26	26	—	7.8 hr	β+
		27	—	8.9 min	β+
		28	6.04	stable	
		29	—	4 years	
		30	91.57	stable	
		31	2.11	"	
		32	0.28	"	
		33	—	47 days	
Co	27	28	—	18.1 hr	γ, β−
		29	—	8 days	γ, β+
		30	—	270 "	γ, β+
		31	—	72 "	γ, β+
		32	100	stable	γ, β+
		33	—	5.3 years	
		34	—	1.75 hr	γ, β−
Cu	29	29	—	7.9 min	β−
		31	—	8.1 sec	β+
		32	—	3.4 hr	β+
		33	—	9.92 min	β+
		34	69.48	stable	β+
		35	—	12.8 hr	γ, β+, β−
		36	30.52	stable	
		37	—	5 min	β−

Note. See note to Table 124.

D. I. MENDELEYEV'S PERIODIC

PERIODS	SERIES	E L E M E N T				
		I	II	III	IV	V
1	I	**H** 1 1,00797 1				
2	II	**Li** 3 6,939 1 2	**Be** 4 9,0122 2 2	3 2 5 **B** 10,811	4 2 6 **C** 12,01115	5 2 7 **N** 14,008
3	III	**Na** 11 22,991 1 8 2	**Mg** 12 24,312 2 8 2	3 8 2 13 **Al** 26,9815	4 8 2 14 **Si** 28,086	5 8 2 15 **P** 30,9738
4	IV	**K** 19 39,102 1 8 8 2	**Ca** 20 40,08 2 8 8 2	**Sc** 21 44,956 2 9 8 2	**Ti** 22 47,90 2 10 8 2	**V** 23 50,942 2 11 8 2
	V	1 18 8 2 29 **Cu** 63,54	2 18 8 2 30 **Zn** 65,37	3 18 8 2 31 **Ga** 69,72	4 18 8 2 32 **Ge** 72,59	5 18 8 2 33 **As** 74,9216
5	VI	**Rb** 37 85,47 1 8 18 8 2	**Sr** 38 87,62 2 8 18 8 2	**Y** 39 88,905 2 9 18 8 2	**Zr** 40 91,22 2 10 18 8 2	**Nb** 41 92,906 1 12 18 8 2
	VII	1 18 18 8 2 47 **Ag** 107,870	2 18 18 8 2 48 **Cd** 112,40	3 18 18 8 2 49 **In** 114,82	4 18 18 8 2 50 **Sn** 118,69	5 18 18 8 2 51 **Sb** 121,76
6	VIII	**Cs** 55 132,905 1 8 18 18 8 2	**Ba** 56 137,34 2 8 18 18 8 2	**La*** 57 138,91 2 9 18 18 8 2	**Hf** 72 178,49 2 10 32 18 8 2	**Ta** 73 180,948 2 11 32 18 8 2
	IX	1 18 32 18 8 2 79 **Au** 196,967	2 18 32 18 8 2 80 **Hg** 200,59	3 18 32 18 8 2 81 **Tl** 204,37	4 18 32 18 8 2 82 **Pb** 207,19	5 18 32 18 8 2 83 **Bi** 208,980
7	X	**Fr** 87 [223] 1 8 18 32 18 8 2	**Ra** 88 [226] 2 8 18 32 18 8 2	**Ac**** 89 [227] 2 9 18 32 18 8 2	**(Th)**	**(Pa)**

*LANTHA

Ce 58 140,12 2 8 20 18 8 2	**Pr** 59 140,907 2 8 21 18 8 2	**Nd** 60 144,24 2 8 22 18 8 2	**Pm** 61 [147] 2 8 23 18 8 2	**Sm** 62 150,35 2 8 24 18 8 2	**Eu** 63 151,96 2 8 25 18 8 2	**Gd** 64 157,25 2 9 25 18 8 2

**ACTI

Th 90 232,038 2 10 18 32 18 8 2	**Pa** 91 [231] 2 9 20 32 18 8 2	**U** 92 238,03 2 9 21 32 18 8 2	**Np** 93 [237] 2 8 23 32 18 8 2	**Pu** 94 [242] 2 8 24 32 18 8 2	**Am** 95 [243] 2 8 25 32 18 8 2	**Cm** 96 [247] 2 9 25 32 18 8 2

Figures in square brackets are mass numbers of stablest isotopes

Note. The table is drawn up in the usual manner : each box con-
it — the atomic weight (the average value of the atomic weights of the
of electrons in the shells in the order *K*, *L*, *M*, *N*, *O*, *P*, *Q*.

TABLE OF ELEMENTS

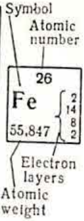
GROUPS					
VI	VII	VIII			0
	(H)				He 2 4,0026 2
8 O 15,9994 6 2	9 F 18,9984 7 2				Ne 10 20,183 8 2
16 S 32,064 6 8 2	17 Cl 35,453 7 8 2				Ar 18 39,948 8 8 2
Cr 24 51,996 1 13 8 2	Mn 25 54,9381 2 13 8 2	Fe 26 55,847 2 14 8 2	Co 27 58,9332 2 15 8 2	Ni 28 58,71 2 16 8 2	
34 Se 78,96 6 18 8 2	35 Br 79,909 7 18 8 2				Kr 36 83,80 8 18 8 2
Mo 42 95,94 1 13 18 8 2	Tc 43 [97] 1 14 18 8 2	Ru 44 101,07 1 15 18 8 2	Rh 45 102,905 1 16 18 8 2	Pd 46 106,4 0 18 18 8 2	
52 Te 127,60 6 18 18 8 2	53 I 126,9044 7 18 18 8 2				Xe 54 131,30 8 18 18 8 2
W 74 183,85 2 12 32 18 8 2	Re 75 186,2 2 13 32 18 8 2	Os 76 190,2 2 14 32 18 8 2	Ir 77 192,2 2 15 32 18 8 2	Pt 78 195,09 1 17 32 18 8 2	
84 Po [210] 6 18 32 18 8 2	85 At [210] 7 18 32 18 8 2				Rn 86 [222] 8 18 32 18 8 2
(U)					

NIDES 58-71

Tb 65 158,924 2 8 27 18 8 2	Dy 66 162,50 2 8 28 18 8 2	Ho 67 164,930 2 8 29 18 8 2	Er 68 167,26 2 8 30 18 8 2	Tu 69 168,934 2 8 31 18 8 2	Yb 70 173,04 2 8 32 18 8 2	Lu 71 174,97 2 8 32 18 8 2

NIDES

Bk 97 [247] 2 8 27 32 18 8 2	Cf 98 [249] 2 8 28 32 18 8 2	Es 99 [254] 2 8 29 32 18 8 2	Fm 100 [253] 2 8 30 32 18 8 2	Md 101 [256] 2 8 31 32 18 8 2	No 102 [255] 2 8 32 32 18 8 2	Lw 103 [257] 2 9 32 32 18 8 2



tains the symbol of an element; above it — the atomic number, below most widespread isotopes) The columns of figures give the number

Table 124

Atomic Weight, Relative Abundance and Activity of Some Light Isotopes

Element	Number of protons	Number of neutrons	Atomic weight	Relative abundance, %	Half life	Type of activity
H	1	0	1.0081	99.98	stable	
D	1	1	2.0147	0.02		
T	1	—	3.0170	10^{-18}	12.26 years	β−
He	2	1	3.0170	1.3^{-4}	stable	
		2	4.0039	~100	″	
		3	5.0137	—	6×10^{-20} sec	α, *n*
		4	6.0209	—	0.8 sec	β−
C	6	4	10.0204	—	8.8 sec	β+, γ
		5	11.0150	—	21 min	β+
		6	12.0039	98.9	stable	
		7	13.0076	1.1	″	
		8	14.0077	—	5568 years	β−
O	8	7	15.0078	—	125 sec	β+
		8	16.0000	99.76	stable	
		9	17.0045	0.04	″	
		10	18.0048	0.20	″	
Al	13	11	—	—	29.4 sec	β−
		13	25.9944	—	7 sec	β+
		14	26.9907	100	stable	
		15	27.9908	—	2.3 min	β−, γ
		16	28.9892	—	6.6 ″	β−

Note. β− — electron, β+ — positron, γ — gamma-rays, α — helium nucleus, *n* — neutron.

Table 125

Some Artificially Produced Elements

Atomic number	Name of element	Mass numbers	Half life
61	Promethium (Pm)	**145**, 146, 147, **148**, 149, 150, 151,	30 years
85	Astatine (At)	206, 208, 209, **210**, 211	8.3 hr
87	Francium (Fr)	212, 221, 222, **223**	21 min
93	Neptunium (Np)	231, 232, 233, 234, 235, 236, **237**, 238, 239	2.25×10^6 years
94	Plutonium (Pu)	232, 234, 236, **237**, 239, 240, 241, **242**, 243	5×10^5 years
95	Americium (Am)	238, 239, 240, 241, 242, **243**, 244	10^4 years
96	Curium (Cm)	238, 240, 241, 242, 243, 244, **245**	500 years
97	Berkelium (Bk)	243, **245**, 246, 247	5 days
98	Californium (Cf)	244, 246, **248**	2, 100 years
99	Einsteinium (En)	253	12 days
100	Fermium (Fm)	255	4.5 days
101	Mendelevium (Mv)	256	30 min
102	Nobelium (No)	263	—

Note. The mass number of the isotope with the greatest half life is given in boldface type.

Table 126

Elementary and Non-Elementary Particles

Particles which, according to present-day notions, are not composed of more fundamental particles are called *elementary*.

Name	Symbol	Mass		Charge, (elementary charges)	Average lifetime, sec
		in atom units of mass	relative to electron mass		
Elementary particles					
Photon	γ, $h\nu$	0	0	0	stable
Neutrino	ν	0	<0.001	0	"
Antineutrino . . .	$\overline{\nu}$	0	<0.001	0	"
Electron	e^-, $\beta+$	5.49×10^{-3}	1	-1	"
Positron	e^+ $\beta+$	5.49×10^{-3}	1	$+1$	stable
L-mesons	μ^+	0.1155	210	$+1$	2.22×10^{-6}
	μ^-	0.1155	210	-1	2.22×10^{-6}
	π^+	0.151	275	$+1$	2.53×10^{-8}
	π^-	0.151	275	-1	2.53×10^{-8}
	π°	0.165	300	0	1×10^{-15}- -5×10^{-15}
K-mesons	K^+	—	966	$+1$	1.27×10^{-8}
	K^-	—	966	-1	1.27×10^{-8}
Nucleons:	K_0^1, K_0^2	—	965	0	1.3×10^{-10}
proton	p, H_1^1	1.00760	1,836	$+1$	stable
neutron	n, n_0^1	1.00899	1,839	0	4×10^3
Antiproton	$\overline{p}$	—	1,836	-1	stable in vacuum
Antineutron . . .	$\overline{n}$	—	1,839	0	"
Hyperons	Λ°	—	2,181.5	0	3.7×10^{-10}
	Σ^+	—	2,327	$+1$	3.4×10^{-11}
	Σ^-	—	2,327	-1	3.4×10^{-11}
Non-elementary particles					
Deuteron	d, H_1^2	2.014	—	$+1$	stable
Triton	t, H_1^3	3.016	—	$+1$	5.6×10^8 sec
Alpha-particle . .	d, He_2^4	4.003	—	$+2$	stable

Notes. 1. Mesons and hyperons are produced in the collisions of high-energy particles (for example, protons and α-particles in the cosmic radiation). These particles disintegrate rapidly to form new particles (electrons, positrons, photons, nucleons, etc.)

2. The antiproton and antineutrino were discovered recently by means of a high-energy particle accelerator.

Table 127

Energies of Some Particles

Particle	Energy, Mev
Maximum energy of β^- (Th C → Th C′)	2.25
" " " β^- (Th C″ → Pb)	1.79
Energy of α-particle (Th C′ → Pb)	8.95
" " α-particle (Th C′ → Th C″)	6.20
" " photon of γ-radiation	3.20
" " cosmic ray mesons (secondary radiation)	10^{-3}-10^{6}
Particles produced in accelerators	
Protons	600-700
Neutrons	500-650
π^+-mesons	150-360
π^--mesons	300-400
μ^+-mesons	90
μ^--mesons	25
Photon of γ-radiation (in decay of π°-mesons)	10-600
" " γ-radiation (in decay of deuterons)	up to 300
" " γ-radiation (in decay of α-particles)	500-600

Notes. 1. The nuclear reactions in which particles of the given energy are produced are given in parentheses.

2. The indicated energies of particles produced in accelerators were obtained in the USSR in the 6-meter proton synchrotron (as of July 1957). More recently protons of energy 10^4 Mev were produced in the high-energy proton synchrotron in Dubna. The maximum particle energy obtained to date is about 3×10^4 Mev (proton synchrotron in Geneva).

Table 128

Energy of a Quantum of Radiation of Different Types

Wavelength	Energy, ev	Wavelength	Energy, ev
1 mm	1.22×10^{-3}	1,000 Å	1.22×10
300 μ	4.1×10^{-3}	100 Å	1.22×10^2
1 μ	1.22	10 Å	1.22×10^3
8,000 Å	1.52	1 Å	1.22×10^4
7,000 Å	1.75	0.1 Å	1.22×10^5
6,200 Å	1.96	0.01 Å	1.22×10^6
5,000 Å	2.44	0.001 Å	1.22×10^7
4,000 Å	3.06	0.0001 Å	1.22×10^8
3,000 Å	4.10		

Binding Energy

On the abscissa axis (Fig. 84) are plotted the mass numbers, on the ordinate axis—the binding energy E/M per nucleon in electron volts. Nuclear energy can be released either by the fission of heavy nuclei or by the synthesis of light nuclei. In both cases new nuclei are produced with a binding energy E/M greater than that of the original nuclei.

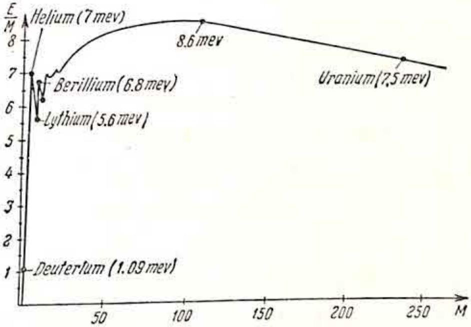


Fig. 84. Curve of binding energy.

Examples of Nuclear Reactions

Nuclear reactions are accompanied by the release or absorption of energy.

In the reactions given below the numbers on the left-hand side of the equations indicate the energy absorbed, on the right-hand side of the equations—the energy released, in Mev.

1. $_{7}N^{14} + {}_{2}He^{4} + 1.1 = {}_{8}O^{17} + {}_{1}H^{1}$
2. $_{3}Li^{7} + {}_{1}H^{1} = 2\,{}_{2}He^{4} + 17.3.$
3 $_{13}Al^{27} + {}_{2}He^{4} + 28.2 = {}_{15}P^{30} + {}_{0}n^{1}.$
4 $_{7}N^{14} + {}_{0}n^{1} = {}_{6}C^{14} + {}_{1}H^{1} + 0.6.$
5 $_{13}Al^{27} + {}_{6}C^{12} = {}_{17}Cl^{34} + {}_{2}He^{4} + {}_{0}n^{1} + 28.2.$
6 $_{90}Th^{232} + {}_{0}n^{1} \rightarrow {}_{90}Th^{233}.$
$_{90}Th^{233} \rightarrow {}_{91}Pa^{233} + e^{-}.$
$_{91}Pa^{233} \rightarrow {}_{92}U^{233} + e^{-}.$

Notes. 1. The arrows in equation 6 indicate that the reaction continues spontaneously.

2. The fission of one uranium nucleus leads to the release of about 200 Mev of energy. The energy released by 1 gram of uranium equals 22×10^{3} kilowatt-hours.

Synthesis of Helium from Hydrogen

The production of helium nuclei by the synthesis (fusion) of hydrogen nuclei is of immense theoretical and practical significance, since in this process a large amount of energy is released.

The following are some of the possible reactions. The energy released is expressed in Mev.

1. ${}_1H^2 + {}_1H^2 \rightarrow {}_2He^4 + \gamma + 23.8.$
2. ${}_1H^2 + {}_1H^1 \rightarrow {}_2He^3 + \gamma + 5.4.$
   ${}_2He^3 + {}_1H^1 \rightarrow {}_2He^4 + e^+ + 18.7.$
3. ${}_2He^3 + {}_1H^3 \rightarrow {}_2He^4 + {}_1H^2 + 14.3.$

Reactions of Nuclear Synthesis

Reactions of nuclear synthesis can take place at high temperatures (millions of degrees). The following are some examples of such reactions.

1. ${}_6C^{12} + {}_1H^1 \rightarrow {}_7N^{13} + \gamma + 1.9.$
2. ${}_7N^{13} \rightarrow {}_6C^{13} + e^+ + 1.2.$
3. ${}_6C^{13} + {}_1H^1 \rightarrow {}_7N^{14} + 7.5.$
4. ${}_7N^{14} + {}_1H^1 \rightarrow {}_8O^{15} + \gamma + 7.3.$
5. ${}_8O^{15} \rightarrow {}_7N^{15} + e^+ + 1.7.$
6. ${}_7N^{15} + {}_1H^1 \rightarrow {}_6C^{12} + {}_2He^4 + 4.9.$

Units of Radioactivity and Radiation

The unit of radioactivity is the *curie*. 1 curie corresponds to the intensity of radiation of radon in a state of radioactive equilibrium with 1 gram of radium. The curie is also a measure of the quantity of a radioactive substance. A *curie* is a quantity of any radioactive substance which decays at the rate of 3.7×10^{10} atoms per second.

The *roentgen* is the unit of X- and γ-radiation.

A *roentgen* is a quantity of radiation which produces in 1 cm^3 of dry air at 0° C and 760 mm Hg a number of ions carrying a total of one electrostatic unit of charge of each kind (2×10^9 pairs of ions).

APPENDICES

I. Some Frequently Encountered Numbers

$\pi = 3.141593$
$4\pi = 12.56637$
$\frac{2}{\pi} = 0.63662$
$\pi^2 = 9.86960$

$\sqrt{\pi} = 1.77245$
$e = 2.718282$
$\sqrt{2} = 1.41421$
$\sqrt{3} = 1.73205$

$1^\circ = 0.017453$ radian
$1' = 0.000291$ „
$1'' = 0.0000048$ „

II. Formulas for Approximate Calculations

$\frac{1}{1+x} = 1 - x$	$-0.031 < x < 0.031$
$\sqrt{1+x} = 1 + \frac{1}{2}x$	$-0.085 < x < 0.093$
$\frac{1}{\sqrt{1+x}} = 1 - \frac{1}{2}x$	$-0.052 < x < 0.052$
$\sin x = x$	$-0.077 < x < 0.077$
$e^x = 1 + x$	$-0.045 < x < 0.045$

The inequalities indicate the range of values of x for which the error of the computations by the approximate formulas does not exceed 0.1%.

III. Elements of the Theory of Errors

All measurements can be performed only up to a certain degree of precision.

Precision is determined by the last significant figure of the measurement. In order to exclude chance errors which are always possible, the measurement should be repeated several times and the mean arithmetic value of all the results taken.

If a quantity A has been measured n times and $A_1, A_2, A_3, \ldots, A_n$ are the results of the individual measurements, then the mean arithmetic value is

$$A_{\text{mean}} = \frac{A_1 + A_2 + \ldots + A_n}{n}.$$

The deviation $\Delta A_i = |A_{\text{mean}} - A_i|$ is called the *absolute error of a single measurement*. The quantity

$$\Delta A = \frac{\Delta A_1 + \Delta A_2 + \ldots + \Delta A_n}{n}$$

is called the *mean absolute error* of the measurement. Usually it is considered that

$$A_{\text{mean}} - \Delta A < A < A_{\text{mean}} + \Delta A.$$

The ratio $\frac{\Delta A}{A_{\text{mean}}}$ is called the *mean relative error* and is usually expressed in per cent.

The result sought by the experimenter is rarely found by measuring only one quantity. It is generally necessary to measure several quantities and to calculate the desired result from a formula. The following table gives expressions for finding the absolute and relative errors of calculations carried out by some frequently encountered formulas.

Formula	Absolute error	Relative error
$A+B$	$\Delta A + \Delta B$	$\left\|\frac{\Delta A + \Delta B}{A+B}\right\|$
$A-B$	$\Delta A + \Delta B$	$\frac{\Delta A + \Delta B}{\|A-B\|}$
AB	$\|A\,\Delta B + B\,\Delta A\|$	$\frac{\Delta A}{\|A\|} + \frac{\Delta B}{\|B\|}$
$\frac{A}{B}$	$\frac{\|B\,\Delta A + A\Delta B\|}{B^2}$	$\frac{\Delta A}{\|A\|} + \frac{\Delta B}{\|B\|}$
A^n	$n\,\|A^{n-1}\|\,\Delta A$	$n\,\frac{\Delta A}{\|A\|}$
$\sqrt[n]{A}$	$\frac{1}{n}\,\|A^{\frac{1-n}{n}}\|\,\Delta A$	$\frac{1}{n}\,\frac{\Delta A}{\|A\|}$

Example. To determine the density of a solid one measures its volume and its mass. Assume that the volume has been measured with an accuracy of 1.5%, and the mass with an accuracy of 1%. Then the relative error of the determined value of the density is 2.5%. Hence, we may write:

$$\left(\frac{m}{V}\right)_{\text{mean}}(1-0.025) < \frac{m}{V} < \left(\frac{m}{V}\right)_{\text{mean}}(1+0.025).$$

IV. Prefixes to the Basic Units of Measure

mega (M)	10^6	milli (m)	10^{-3}
kilo (k)	10^3	micro (μ)	10^{-6}
deci (d)	10^{-1}	nano (n)	10^{-9}
centi (c)	10^{-2}	pico (p)	10^{-12}

The figures in the right-hand column indicate the number of multiples and sub-multiples of the basic unit which are formed by attaching the prefixes. For example, 1 Mc/s $=10^6$ c/s; 1mm $=10^{-3}$ m.

V. Units of Measure of Some Physical Quantities

Mass

1 ton $=10$ centners $=1{,}000$ kilograms.
1 carat $=2\times10^{-4}$ kilogram.
1 pood $=16.38050$ kilograms.

Length

1 micron $=10^{-6}$ m.
1 Å (Angstrom unit) $=10^{-8}$ cm.
1 X $=10^{-11}$ cm.
1 inch $=25.40$ mm.
1 foot $=0.30480$ m.
1 yard $=0.91440$ m.
1 mile (English) $=1{,}609$ m.
1 mile (nautical) $=1{,}852$ m.
1 light year $=9.463\times10^{12}$ km.

Time

1 year $=31{,}556{,}925.975$ sec.
1 day $=24$ hours $=1{,}440$ min $=86{,}400$ sec.
1 hour $=60$ min $=3{,}600$ sec.

Pressure

1 atmosphere (technical) $=1$ kg/cm$^2=735.66$ mm Hg.
1 mm Hg $=0.001316$ atm $=1{,}333$ dynes/cm$^2=133.3$ N/m^2.
1 atmosphere (standard) $=760$ mm Hg $=1.033$ kg/cm$^2=1.013\times10^6$ dynes/cm$^2=1.013\times10^5$ N/m^2.

Temperature

Number of degrees centigrade (°C) $=5/4°$ R $=5/9$ (°F -32) $=$ (°K -273).

Here °R denotes the number of degrees on the Réaumur scale, °F — the number of degrees Fahrenheit, °K — the number of degrees Kelvin.

Thermal Conductivity

1 kilocal/m hour degree $= 2.778\times10^{-3}$ cal/cm sec degree $= 1.162\times10^{-2}$ watt/cm degree.

Work and Energy

1 watt-hour = 3,600 watt-sec.
1 joule = 1 watt-sec $= 10^{7}$ ergs = 0.239 cal (calorie).
1 kg m (kilogram meter) = 9.81 joules.
1 kilocal (kilocalorie) = 1.16 watt-hours.
1 ev (electron volt) $= 1.6019\times10^{-12}$ erg $= 1.6019\times10^{-19}$ joule.

Power

1 watt $= 10^{7}$ erg/sec.
1 kilowatt = 102 kg m/sec = 1.36 hp (horsepower).

Capacitance

1 cm = 1.11 picofarad $= 1.11\times10^{-12}$ farad.

VI. Universal Physical Constants

Gravitational constant γ . .	6.67×10^{-8} g^{-1} cm^{3} sec^{-2} 6.67×10^{-11} kg^{-1} m^{3} sec^{-2}
Volume of one grammolecular weight of an ideal gas under standard conditions V_{μ} . .	22.4207 liters
Universal gas constant R .	8.31696 joule degree^{-1} mole^{-1}
Faraday's number F	96.521 coul/g-equiv
Avogadro's number N . . .	6.02497×10^{23} mole^{-1}
Boltzmann's constant k . .	1.38041×10^{-16} erg degree^{-1}
Mass of hydrogen atom m_{H}	1.67339×10^{-24} g
Mass of proton m_{p}	1.67239×10^{-24} g
Mass of electron m_{e}	9.1083×10^{-28} g
Charge of electron e	4.80274×10^{-10} CGSE 1.60202×10^{-20} CGSM
Velocity of light in vacuum c_0	2.99793×10^{10} cm sec^{-1}
Planck's constant h	6.62517×10^{-27} erg sec
Rydberg's constant for hydrogen R_{H}	109,677.576 cm^{-1}
Rydberg's constant for deuterium R_{D}	109,707.419 cm^{-1}
Rydberg's constant for helium R_{He}	109,722.267 cm^{-1}

VII. SI and CGS

The following table gives the names, designations and dimensions of the most frequently used units of the SI system.

The last two columns give the conversion factors for the CGSE and CGSM systems.

For mechanical units the CGSE and CGSM systems coincide fully; the fundamental units of these systems are: the centimeter, gram (mass) and second.

The two systems differ for electrical quantities. This is due to the circumstance that the fourth fundamental unit in the CGSE system is the permittivity of vacuum ($\varepsilon_0=1$), and in the CGSM system—the permeability of vacuum ($\mu_0=1$).

Quantity	Unit	Dimensions	Conversion factors relating MKSA units to	
			CGSE	CGSM
		1. Fundamental units		
Length	*meter*, m	m	10^2 cm	10^2 cm
Mass	*kilogram*, kg	kg	10^3 g	10^3 g
Time	*second*, sec	sec	1 sec	1 sec
Current	*ampere*, amp	amp	3×10^9	10^{-1}
		2. Mechanical units		
Velocity	*meter per second*, m/sec	m/sec	10^2 cm/sec	10^2 cm/sec
Acceleration	*meter per second per second*, m/sec^2	m/sec^2	10^2 cm/sec^2	10^2 cm/sec^2
Energy and work	*joule* or *watt per second*, joule	kg m^2/sec^2=joule	10^7 ergs	10^7 ergs
Force	*newton*, N	kg m/sec^2=joule/m	10^5 dynes	10^5 dynes
Power	*watt*, w	kg m^2/sec^3=joule/sec	10^7	10^7

3. Electrical units

Charge	*coulomb*, coul	amp sec=coul	3×10^{9}	10^{-1}
Potential, e. m. f.	*volt* v	kg m^2/amp sec^3=v	1/300	10^{8}
Electric field intensity	*volt per meter*, v/m	kg m/amp sec^3=v/m	$1/3\times10^{-4}$	10^{6}
Capacitance	*farad*, fd	amp^2/sec^4/kg m^2= =amp^2/sec^4/v= =sec/ohm	9×10^{11} cm	10^{-9}
Resistance	*ohm*, ohm	kg m^2/amp^2 sec^3= =v/amp	$1/9\times10^{-11}$	10^{9}
Resistivity	*ohm meter*, ohm m	kg m^3/amp^2 sec^3= =ohm m	$1/9\times10^{-11}$	10^{11}
Permittivity	*farad per meter*, fd/m	amp^2 sec^4/kg m^3=fd/m	$36\pi\times10^{9}$	$4\pi\times10^{-11}$

4. Magnetic units

Magnetic flux . .	*weber*, wb	kg m^2/amp sec^2	1/300	10^{8} maxwells
Magnetic induction .	*weber per square meter*, wb/m^2	kg/amp sec^2	$1/3\times10^{-6}$	10^{4} gauss
Magnetisation . . .	*ampere per meter*, amp/m^2	amp/m	3×10^{7}	10^{-3} gauss
Magnetic field intensity	*ampere per meter*, amp/m	amp/m	$12\pi\times10^{7}$	$4\pi\times10^{-3}$ oersted
Inductance	*henry*, henry	kg m^2/amp^2 sec^2= =ohm sec	$1/9\times10^{-11}$	10^{-9} cm
Permeability	*henry per meter*, henry/m	henry/m	$\frac{1}{36\pi\times10^{13}}$	$\frac{1}{4\pi}\times10^{7}$

5. Optical units

Radiant flux	*lumen*, lumen	candela steradian	—	—
Luminance	*candela per square meter*, candela/m^2	candela/m^2	—	—
Illuminance . . .	*lux*, lux	lumen/m^2	—	—

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TO THE READER

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